NTNU
Norwegian University of Science and Technology

Life cycle assessment of a pumped storage power plant

Octavio Torres

Master in Industrial Ecology
Submission date: July 2011
Supervisor: Edgar Hertwich, EPT
Co-supervisor: Jan Weinzettel, EPT

Norwegian University of Science and Technology
Department of Energy and Process Engineering

Después de la lluvia llega la calma y vice versa

Acknowledgment

Thanks:

For the support of all the people who have been part of this journey without you this wouldn’t have been as entertained and exiting to fulfill.

To my office mates with whom I had the chance to discuss and share different point of views

To both of my supervisors and external contacts Edgar and Jan, who were always open to discuss and structure of the work and provided useful insights upon on it

To Livi whose support and companionship has been vital during this stage of the journey

To the life we live

Table of Contents

Appendix

List of Tables

List of figures

Abbreviations

GHG greenhouse gases

IEA International Energy Agency

CO_2 Carbon dioxide

CH_4 Methane

ppm parts per million

IPCC International Panel for Climate Change

EU European Union

NVE Master Plan for Water

WTP Willingness to Pay

LCA Life Cycle Assessment

Cedren Center for Design of Renewable Energy

LCI Life Cycle Inventory

NiMH Nickel metal hydride

NCM nickel cobalt manganese lithium-ion

LFP iron phosphate lithium ion

C-D cycle Charge Discharge Cycle

1. *Motivation & Trends*

Energy storage is becoming an increasingly relevant service due to the considerable expansion since the past decade of the generation of energy from renewable sources as a strategy for dismantling of the greenhouse gas emission (GHG) and assurance of a secure supply of energy, as a response to inevitable depletion of nonrenewable fossil fuels as oil. A considerable portion of the renewable energy produced nowadays comes from fluctuating sources as sun and wind, being this fluctuation a barrier for the full integration of the renewable sources into the grid system. In recent years pumped storage hydro plant has come into scene as a plausible solution to ensure a constant energy output from renewables into the grid. Pumped storage hydro plant is the most widespread storage system used, nowadays it is becoming even more attractive as an option to provide ancillary services to renewable and it is achieving higher penetration into the energy market. As a consequence understanding its environmental performance has become a must of strategic importance. This can be fulfilled by evaluating the pumped storage hydro plant life cycle environmental performance, which would result in an in depth resolution upon the environmental stressors emitted, providing at the same time hints to improve the overall environmental performance of the system.

The main objective of this master thesis is to analyze a set of environmental stressors produced during the life cycle of the pumped storage hydro plant.

1.1. Background

At the end of the past decade the International Energy Agency (IEA) starks a clear message, in which it calls urgently for a shift on the energy policies and practices worldwide, with the aim of dismantling a big proportion of the anthropogenic emissions (IEA 2009). Nowadays the life cycle of the energy system accounts for two thirds of greenhouse-gas emissions (GHG), being this situation recognized as the heart of a critical problem titled as *climate change* and the core for a tangible he solution.

Table 1 Breakdown of the main Anthropological emissions generated in 2008 (IEA 2008)

Anthropogenic Emission[1]	**Percentage**
CO2 Fossil fuel use	56.6%
CO2 Deforestation decay of biomass, ect	17.3%
CO2 (other)	2.8%
CH4	14.3%
NOx	7.9%
F-gases	1.1%

On perspective GHGs have increased by an average of 1.6% per year, carbon dioxide (CO_2) emissions from the use of fossil fuels growing at a rate of 1.9% per year, while in aggregate levels there has been an increase of 279 particles per million (ppm) of CO_2 between preindustrial times and (the year) 2005(EU & ESMIG 2008). This increase of anthropogenic emissions has led to a widespread increase of temperature over the globe during the last century, with the average increase on temperature 0.74Centigrades (Bernstein et al. 2007)

The Intergovernmental Panel on Climate Change (IPCC) has projected a further increase of GHG emission following the continuous growth of the global energy demand. Combustion of fossil fuels[2] still dominates a global energy market that is striving to meet the ever-increasing demand for heat, electricity and transport fuels.

[1] *Manmade emission, number source Alternative Energy: 2008 outlook*

[2] *Global dependence on fossil fuels has led to the release of over 1100 GtCO2 into the atmosphere since the mid-19th century. Currently, energy-related GHG emissions, mainly from fossil fuel combustion for heat supply, electricity generation and transport, account for around 70% of total emissions including carbon dioxide, methane and some traces of nitrous oxide (Smil 2006).*

Without a near-term introduction of supportive and effective policies by governments, energy related GHG emissions, mainly from fossil fuel combustion, are expected to rise by over 50%, from 26.1 GtCO_2eq (7.1 Gtons) in 2004 to 37–40 GtCO_2 (10.1–10.9 Gtons) by 2030. Mitigation has therefore become even more challenging. Following this line the European Union has established the target of achieving a 20% share of renewable energies in the overall energy mix by 2020.

These facts provide an infallible picture of the present reality, and calls for speeding up the transition of the energy system. This shall be done through the whole life cycle of the system, by accelerating the pace of a transition of the primary energy production sources, and transforming the way energy is consumed.

An aspect that can't be left aside concern the main objectives of every energy system which are: a wide range of energy sources and carriers, long term security over supply, affordability and emission of the minimal environmental impact. The main challenge consists in using the existing energy resources in an environmentally acceptable manner while ensuring the provision and security for the needs of the growing population and the development of the economies worldwide.

At the present time several tendencies, which call for, transition solutions, among them there is the imminent arrival of an oil peak phenomenon. In this sense the development, implementation and further integration of new and well known energetic technologies would allow a secure energy provision for years ahead.

During the last years the pronounced intensification of the installation of wind and solar power plants to cut down the GHG emissions and extend energy security production, has increased the attention on energy storage systems as a long-term solution to the intermitted production problems inherent on this type of technologies.

Pumped storage hydro plant is catalogued as one of the most reliable large-scale energy storage. Many plants have being operating for several decades, making this a mature and well-known technology, able to provide several other ancillary services.

An appraisal of the environmental impacts occurring during the life cycle *(construction, operation and dismantle phases)* of this technology is relevant (to the decision making process) in order to avoid possible environmental shifting problems, while estimating the mitigation potential of the system under appraisal.

1.2. Landscape of energy system

The production of energy has become of essential importance to mankind during the last two centuries, to the point that is possible to reconstruct modern society history having as a basis the evolution and reinvention of energy sources, and the way energy has been employed. Energy plays a central role in our daily routine, being an essential requirement to develop the most obvious and simple activities, as the preparation of food and provision of heat (in order to make life more comfortable).

Throughout history, mankind has employed several energy-carriers for satisfying primary and basic needs. A quick retrospective overview of those drive us back to the primary use of wood[3] and its incineration for the production of heat, a bit later to the production of charcoal[4] from wood as a replacement due to its higher heating value per weight. Later in time it appears coal extraction and its incineration. Coal is a solid material rich in carbon; there are several types, each of them with different energy content. In the present time coal constitutes the largest fossil fuel resource worldwide and still is one of the most important energy sources

---

[3] *Still is some remote areas wood is being store and then burn during winter to heat up or uses as fuel for cooking.*

[4] *Charcoal is produced from wood, by heating it under oxygen-poor conditions.*

in several regions, being the least expensive fossil fuel. From coal it's possible to produce coke; this is done through a similar process to the one used for/in the production of charcoal. Coke, when it's burned, has more heat per weight and volume unit than coal, it has been employed as fuel for operating the first steam engines while nowadays it is employed in the metallurgical process for the production of iron and steel (Huggins 2010).

Later in history was achieved the exploration and extraction of petroleum and natural gas as by-product, followed by the industrial production of kerosene, trigging an industrial and technological boom. This boom has continued until now, but at the same time it has carried several side effects[5].

The introduction of industrial production and internalization of energy consumption has created a social economic reality whose axis is an accumulation of wealth and affluence, leading to a self-perpetuation generation of economic growth; this to the point that all of the so-called primary needs are completely supplied. However it should be specified that this reality it's experienced only by a sixth of the whole population. Some tradeoffs from this industrialization process had been generated, where the levels of anthropological emissions have increased to a level never experienced before, and those extra emissions into the environment are unbalancing the homeostasis of planet earth. Among the various consequences there is the climate change phenomenon, which is a consequence of the increase of greenhouse gases emission into the atmosphere. This phenomenon has brought into light the question of how to dismantle those emissions while providing continuity to the social economic dynamics.

As a counter active response alternative energy sources have gradually emerged, starting to supply over the existing energy demand. A growing proportion of the

---

[5] *In this document only the environmental side effect would be inquired in-depth, but this does not means that they are more important than the social or economic ones t. At the need of the story those three side effects are intertwined.*

alternative energy comes from solar and wind technologies. These technologies are highly dependent on external factors, being intermittent sources of production of energy. The supply of energy from these sources is 100% dependent on nature. While solar systems cannot generate power during night time and their output would decrease during cloudy and rainy days, wind power systems are incapable of producing energy if there is lack of wind; similar problems affect water systems which energy production can be disrupted by floods. Fluctuations of output power due to meteorological condition lead to less reliability of the power supply. Uchiyama (2007) call this type of energy sources as *"parasitic electric power sources",* due to their incapacity to supply stable power by themselves, and usually their imbalances have to be compensated by running up fossil fuel based power plants. Though this intermittent production can be replaced by other renewable energy sources as water, nuclear[6], geothermal ect... this depends on the specific energy layout of the region where the energy system is located.

Even though these are intermittent energy sources, nowadays they appear to be the strongest candidates to become the future of the energy supply. And this is closely related to the willingness of dismantling GHG emission from the energy production and consumption. This trend is being supported by policies in several places of the world, as an example the European Union (EU) community has committed to/subscribed the "20-20-20" targets, which aim to increase the supply of energy from renewable sources, while assuring a reduction of at least 20% of the emission level of GHG recorded in 1990 (EU & ESMIG 2008). Other facts supporting the use of intermittent energy to instead of conventional energy sources (fossil fuels based) are associated to the security of energy supply in the future. Fossil fuel, in specific crude oil, is a scare resource, which implies that the peak of the "oil age" production is gradually approximating (Deffeyes 2010). Crude oil has been

[6] *"Nuclear Power can be considered as an environmental friendly production source of energy if the decommission phase of the fuel is not taken into account."*(Gagnon 2002)

employed during the past half century as raw material for the production of petrochemicals, which nowadays are a main part in our daily live, making it possible to state that techno-societies have become “completely” dependent on oil.

At first Challenges shall be addressed to improve the interaction of the intermittent energy sources with the grid. As a matter of fact the amount of energy entering the grid from these sources usually does not exceed 20% of the total demand, due to the fluctuation in their voltage and frequency; while around 80 % of the total output of energy from these sources is lost (Uchiyama 2007). One way to control the power balance in a network is to store the surplus of energy. Energy storage mechanism can match the production with the demand of energy. Transforming the intermittent energy sources from *“parasitic electric power sources”* into “co-operative energy systems” pumped storage hydro plant provides the possibility of recovering the energy surplus; it permits as well to run the hydropower mode during energy peak hours due to its fast response.

In the future countries as Germany, who has committed to dismantle its nuclear energy facilities before 2020, while steadily increasing the install capacity of renewable energy, would require energy storage services, *(due to the external factor and time dependency matching needed between demand and availability of this resource)* (Evans 2011). This translates for countries as Norway in the opportunity to provide resource management or load management of renewable energy, considering the huge potential of this country to transform hydropower plants into storage facilities, and so to provide this type of service to countries as Germany.

1.3. Review of energy storage technologies

There are several types of energy storage that are capable of providing this service according to specific requirements as; type of technology used, facility size, power quality, bridging power and energy management capacities (life efficiency per cycle cost). These categories allow discriminating between storage technologies and mechanism and their economic feasibility for their usage depending on the energy storage needs (ESA 2009). Regarding the type of technology these systems can be classified as *Advance Battery Systems, Fluid Storage, Mechanical Systems, Electro-magnetic Systems, and hydrogen for energy storage Systems* (Naish et al. 2008)[7].

Next, are reviewed some of the storage technologies that can contribute to the electricity transmission and distribution, mainly by acquiring their energy from large-scale energy and distribution grid and allowing improving the efficiency of electrical energy utilizations. Other benefits beside storing energy are: the stabilization of energy market by providing security through the enhancement of the diversification of the generating sources, the stabilization of transmission and distribution of the grid potentially allowing the reduction of required fossil fuel reserve plants (by reducing the necessity for "spinning reserve", providing "black start capacity")(TEPCO. 2011), and last but not least the optimization of intermittent renewable energy production sources.

1.3.1. Compress Air Energy Systems (CAES)

It's a variation on gas turbines power plants that allows consuming 40% less of gas than in conventional gas turbines. It utilizes the low cost electricity from the power grid at off peak times. It generates electricity when it requires, resulting in a gas reduction of 60% relative to the generation of the same amount of electricity directly from gas (ESA 2009). The reported efficiency of this technology is 80%

[7] *Some of the Characteristics of energy storage devises are (Naish et al. 2008):*
Energy density:" Capacity of energy supply of the technologies per unit of weight (W/kg), defining the energy2(?) that the device can take and deliver"
Time of discharge: "Maximum period of time in which the technology can release the energy store (kW/MW)"
Energy Rating: "determine for how long the device can supply energy, how much energy can be released in a predefine set of time (kWh MWh)."

(Naish et al. 2008). The environmental impact associated to this technology is related to the need of suitable location for underground air storage.

1.3.2. Flywheels

The energy storage provided by this technology is based on a mechanical mechanism where the kinetic energy of a fast spinning cylinder contains considerable stored energy. This type of technology has an expected life of 20 years on average, does not require a lot of maintenance, and provides long-term storage. The energy efficiency is around 90% (ESA 2009).

1.3.3. Superconducting Magnet Energy Storage

This technology stores the electrical energy in a magnetic field, inside a cooled super-conducting coil; its main characteristic is the capacity of a fast discharge calculated around 1 second, while its energy efficiency is up to 97% (Naish et al. 2008). Concerning the environmental aspect, this type of technology requires extremely low temperatures, which implies a high demand of energy, there is as well a risk related to magnetic radiation issues.

1.3.4. Lead Acid batteries

One of the most common and oldest battery technologies, it has a very limited life cycle. Lead batteries are electrochemical cells, based upon chemical reaction involving lead and sulfuric acid lead. The efficiency of this technology is between 60-95% (Naish et al. 2008). The environmental impacts related to this technology are due to the toxicity of the lead, which must be recycled, and the batteries have a high explosion risk.

1.3.5. Lithium batteries

These are electrochemical cells, available in two different types: Ion or Polymer base. This technology has a perfect efficiency of 100% reported (ESA 2009). Concerning its environmental impact, during their end-of use phase they are dismissible due/thanks to the possibility of recycling the lithium oxides and salts

1.3.6. Lead-Acid Batteries

They are electrochemical cells that involve lead and sulfuric acid in a chemical reaction. They represent the oldest and best technology development of electrochemical batteries. The efficiency of these batteries is 60-96%, with self-discharge rates of 4% per month (ESA 2009). The environmental impact is associated to the high toxicity of lead and the corrosive properties of the sulfuric acid.

1.4. Description of Pumped storage hydro plant

1.4.1. History

Pumped storage hydro plant is a mature technology for energy storage. It was employed for the first time in the Italian and Switzerland Alps during the first decade of the 20-century. The first Pumped storage hydro plant was constructed in Schaffhausen, Switzerland; it started operations on 1909 and is still operating at the present. These facilities became more and more attractive during the last century as a source for supplying peak energy[8].

1.4.2. Technology description

Pumped storage hydro plant allows to store and generate energy is a mechanical storage mechanism, which stores potential energy from water that is raised against gravity, employing the gravitational differences between two water storage reservoirs. The way it operates is by pumping the water through a turbine from a lower reservoir to a higher one. For doing this it needs an input of electricity in order to run the pumped mode. Then, when there is a requirement for production of electricity the water is allowed to flow back through a turbine from the higher reservoir back to the lower.

---

[8] *Peak energy makes reference to the portion of the energy demand that is characterize by sharp fluctuations, short period demand, in order words this takes place during the time of the day when the demand for energy (electricity) is the highest, and this extra demand oversets the capacity of the grid in that moment.*

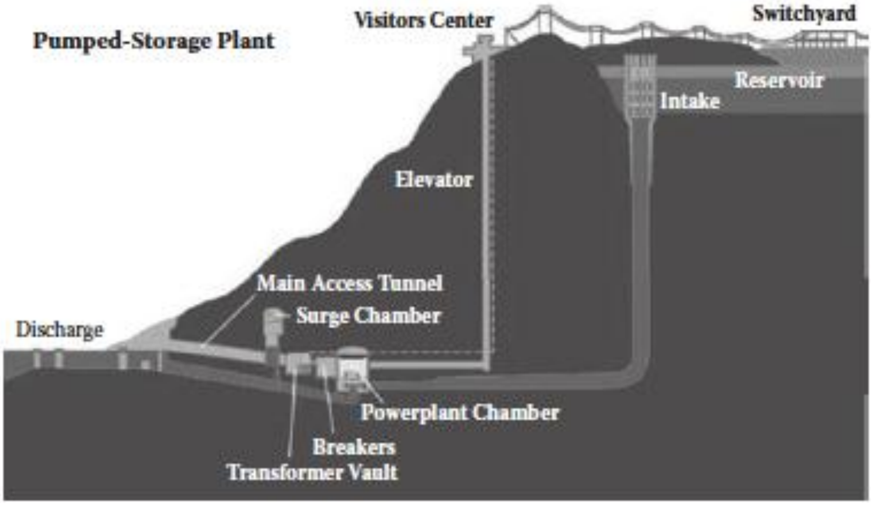


Figure 1 Set up of Pumped Storage Hydro Plant (Levine & Barnes 2011)

The pumped storage hydro plant requires two resources for its operation: the elevation change that is known as the Head and the availability of water, that determines the power and the energy availability of a facility and is given by the potential energy that is produced by potential energy, given by the next equation

$$Potential\ energy = mass * gravity * Hydraulic\ Head$$

The origin of the input of electricity required to run up the pumped mode is the extra margin of electricity being produced to supply the demand in a specific point of the day. This extra margin can be supplied by a coal power plant, gas turbine, wind or sun, or even nuclear (Naish et al. 2008; WIlson & Gwynn 1971; Fry et al. 1969). The greater the amount of renewable energy of the system, the bigger the possibility to have renewable electricity feeding the storage facility, but at the same time this would require a feedback on how an increase of the production of electricity from renewable intermittent source would need more extra capacity of storage (Levine & Barnes 2011). Besides providing a direct support to the increase of the generation of energy using intermittent technologies, pumped storage hydro plant provides the possibility of leveling the price of electricity in the market, by being used in connection with daily peak shaving, load leveling as well as weekly and seasonal variations (Huggins 2010).

The set-up of generic pumped storage hydro plant is presented below; throughout there are several variances depending on the site where it is constructed.

1.4.3. Technology Efficiency

The pumping mode of the plant and the further turbine mode present some losses on the return of energy because not all the water that has been pumped would return as usable electric energy. The efficiency losses of the system are a consequence of:

- the rolling resistance
- the turbulence in the penstock and in the tailrace,
- leakages of the reservoir and around the turbine,
- flow fluctuation due to summer or winter seasons
- aspects related to the electro-mechanic unit (pumping & turbine mode).

The overall efficiency of the technology is reported to be close to 80%. (Huggins 2010; Levine & Barnes 2011) In the following table is possible to observe some of the efficiency losses that have been reported.

Table 2 Overall Efficiency of a Pumped Storage Hydro Plant (H. Chen 1993)

Pumped Storage ρ (cycling)	***Low %***	***High %***
Generating Components		
Water conductors	*97,4*	*98,5*
Pump Turbine	*91,5*	*92*
Generator motor	98,5	99
Transformer	99.5	99,7
Subtotal	*87.35%*	*89.44%*
Pumping component		
Water conductors	97,6	98,5
Pump turbine	91,6	92,5
Generator motor	98,7	99
Transformer	88,5	99,8
Subtotal	87,8	90,02
Operational	98	99,5
Total	**75.15%**	**80.12%** [9]

1.4.4. Pros & Cons of Pumped storage hydro plant technologies

Below are listed some of the benefits and disadvantages related to pumped storage hydro facility

<u>Advantages</u>

-Start up time is of few minutes, fast respond on turning on turbines.
- Rapid response to offset generation variability
- Store energy output during lower value periods
- Prevent wind curtailment and avoid new transmission investments
- “Shape” prices by optimizing schedules of wind output and storage
- Allows for better integration of renewable into the system
- Opportunities of utilizing energy/power storage as solutions for ensuring a constant output of energy from renewable production sources as wind, solar and others
- Expand reserve capacity to protect the system of load conditions where faults cause load excess.
- Low operation and maintenance requirements

[9] *The values have been obtained from (H. Chen 1993)*

Disadvantages

- Requirement of large volume of water resources
- Requirement considerable amount of land and with specific type of conditions
- Construction of reservoirs and dams is resources intensive and expensive
- Is highly dependent of location, can't be constructed anywhere.

2. *Literature review*

2.1. Existing environmental appraisal of pumped storage hydro plant

In this chapter is presented an overview of the state of the art of environmental assessments that have been performed in recent years. A quick summary of each one is provided. Since it hasn't been found any Life Cycle Assessments (LCA) studies performed on pumped storage hydro this review presents several LCA done for hydropower plants, some standard environmental impact analysis performed to this facilities, an LCA performed to electricity storage technology and last a review of a set of most relevant impact categories to be evaluate for a pumped storage hydro facility

2.1.1. Integrating Economic Valuation to life cycle assessment for sustainable energy production & LCA of Norwegian Hydroelectricity-Summary Report

(Vold & Magnussen 1996), (Vold et al. 1996)

Type of assessment: Review of current economic valuation techniques covering environmental impact at Hydropower development Master Plan for Water (NVE); Willingness to Pay (WTP) in marginal changes in quality and quantity of environmental goods; Hedonic Price method observe market behavior regarding the environmental good; Cost benefit measure to environmental improvements

System description: Reservoir hydropower plan, based on the case of study Jostedalen, distribution system is being considered

End use application: Service

Type of use: Foreground study with Functional Unit of 1kWh produced

Environmental impact

Regime and its impact with degree of regulation and draining

- Carbon dioxide CO_2

- Nitrate oxides NO_x
- Sulfur dioxide SO_2
- Fluoride
- Resource depletion of fossil fuel and copper

Data: Environmental Priority Strategies (EPS) Eco-scarcity Method BUWAL, Normalization to person equivalents of total Norwegian Environmental impact

Comments and results: Current Valuation method does not include all the environmental potential impacts connected to hydropower and to LCA. The most important emissions are CO_2, SO_2 and NO_x, and particulate and the depletion of copper and fossil fuel. The distribution system contributed a bit more than the electricity production plant, in most environmental impacts categories beside NO_x.

LCA is not suitable for the quantification of an environmental impact from the production of hydroelectricity

2.1.2. Environmental Declaration ISO/DIS 14025 Type III

(Statkraft & Ostfold 2006) Statkraf EPD foundation Norway, 2007

Type of assessment: Environmental Product Declaration of Trollheim Hydroelectricity power station ISO 14025

System description: Trollheim Hydroelectricity power plant

Type of use: Foreground Functional Unit 1kWh at Trollheim power station

Environmental impact: Midpoint result indicators:

- Nitrification
- Ozone Formation
- Ozone depletion
- Acidification
- Global warming Emissions to air: CO2, CH4 N2O NOx SOx COC CO
- Emissions to water: Tot-N, Tot-P, COD
- Waste: hazardous, recycling, land filli*ng*

Data: Ostfold research Life cycle inventory (LCI)

Comments and results: CO_2 and methane (CH_4) emission due to inundation of land are not included in the data of operation and maintenance of the facility. The construction phase of the facilities accounts for over 50% of the potential emission at each midpoint category evaluated.

2.1.3. Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries (2007)

(Bauer et al. 2007)

Type of assessment: LCI Ecoinvent Data Set Benchmark between LCI country specific at UCTE countries between Reservoir, run of and pumped storage hydro plan

System description: Reservoir Hydropower plant, Run of Hydropower plant and Pumped storage hydro plant are analyzed, no further information regarding the inventory employed.

Type of use: Characterization of the Foreground production system

Environmental impact: GHG from electricity production at reservoir power plant, particle emissions (<2.5 µm).

Data: LCI data set Build from Ecoinvent database

Comments and results: Environmental impacts are highly dependent on the location of the plant and the system. The biggest CO_2 -equiv/kWh emissions happen in Finland during the operation of Reservoir power plant. Overall GHG emitted are bigger at reservoir power plant than run of. The emission of Particle Mater is greater at Run of river plants happening during operation phase. There is not available benchmark about Pumped storage hydro plant (behavior should be similar to that of reservoir) GHG emission at reservoir ought to be “reworked”. Net emissions are highly dependent on plant specific conditions: temperature, type and amount of flooded biomass, reservoir depth, type of soil)

2.1.4. Setting up life cycle Models for the environmental analysis of hydropower generation, considering technical and climatic boundary conditions

(Schuller & Albrecht 2008)

Type of assessment: Setting up life cycle models for environmental analysis of electricity generation by hydropower. The assessment is country specific climatic and vegetal boundary. Vegetal boundary according to country specific at EU 21, Switzerland, Norway, Iceland, Serbia, United States of America, Canada, Brazil, Australia, New Zealand

Assumptions: Biomass degradation at dam (depending on climatic boundary conditions) -Cold Moderate Region CO2 emission increases during the first 5 years and decreases afterwards -Tropical region CH4 emission increases for due to the anaerobic degradation during the first 10 years

System description: Reservoir Hydropower plant, Run of Hydropower plant and Pumped storage hydro plant Dam Comparison: Earth-rock fill VS concrete

Type of use: Foreground Functional Unit 1kWh electric energy

Environmental impact: GHG emissions during operation (Biomass degradation) are taking into account Mid-Point (without electricity supply) -Acidification Potential

Data: Ecoinvent life cycle inventory database

Comments and results: Schuller & Albrecht (2008) presents a global material function –linear approximation- Pumped and Reservoir plant have the biggest GWP emissions, Being operation the phase that emits over 70 % of total emissions. For the acidification potential at the run of river plant the production phases doubles the emissions of the pumped storage plant and reservoir plant emissions. Pumped plant shows higher AP than reservoir due to additional stainless steel used at pumps GWP at site specific during operation phases. The highest emission of GHG is reported in Brazil, being over 20 times bigger than Germany. Concrete Dams have a bigger GWP than earth rock fill for 7 perceptual points, this taking place during the production of concrete.

2.1.5. Environmental and Health Impact of electricity Generation- a comparison of the environmental impact of hydropower with those of other generation technologies

(Husebye 2002)

The Type of assessment performed is a review of Life cycle studies on hydropower plants.

System description: Overview and reference of several set of life cycle inventory from reservoir on run of plants (regarding specific cases in Sweden and Japan), being electricity produced the end use application.

Type of use: Characterization of the Foreground production system

The environmental impact appraisal in a global perspective has been evaluated for:

- Global warming potential (GWP),
- Ozone Depletion Potential (ODP)

In respect with the GHG emission related to the reservoir power plants, it is provided a review of several studies and a further discussion. Among the others the one performed by Gagnon & Vate (1997) where several studies report emission to 2 per kWh produced. The emissions from the manufacturing and the construction phase are supposed to be low and mainly emitted during the manufacturing of the cement and the transportation of the building material.

The Local and Regional environmental impacts evaluated in this assessment are:

- Acidification potential
- Eutrophication potential
- Photochemical oxidant formation
- Ecotoxic impact
- Land change Habitat alterations
- Local climate, Geophysical, Aquatic Impact on biodiversity

- Global & Local Impact on humans
- Health risks Social and socio-economic impact
- Inundated land -Resettlement (river regulation)¨
- Fishing restraints
- Cultural Aesthetic impact -Visual -Acoustic
- The data used are from Ecoinvent and EPS

Comments and results: A review provides the results of the studies carried out by Bränström-Noreberg (1995) on three Swedish plants that have rock filled dams, and of the study by Uchiyama (2007) on Japanese hydroelectric power plants that have dams made of cement.

Table 3 Results of LCA environmental appraisal performed to two hydropower plants

Study	*Substance*	*Unit*	*Manufacturing and Construction*	*Operation and Maintenance*	*Total*
Bränström & Noeberg (Sweden)	Carbon dioxide	*g/kWh*	*4,74 -E01*	*1,02-E01*	***5,76-E01***
	Methane	*g/kWh*	*6,89-E01*	*7,45-E01*	***7,45-E01***
Uchiyama (Japan)	Carbon dioxide	*g/kWh*	*1.70E+01*	*0,26*	**17,2**
	Methane	*g/kWh*	*0,4*	*0.00E+00*	**0,4**

A critical review performed by Cagnon & Chamberland (1993) point outs that the results obtained by Rosenberg et al. (1995), who showed that the GHG potential due to the decomposition of organic matter that results in methane, is 21 times the CO2, have led to results where the emission from hydropower dams is comparable or even exceed that from fossil power plants; mainly pointing out that the factor used to transform the GHG potential of methane to carbon dioxide was incorrect.

Another aspect pointed by (Cagnon & Chamberland 1993) is the need to measure the GHG emission emitted by the land flooded due to overload of a reservoir. Meanwhile (Husebye 2002) noted that hydropower in arid regions contributes to a net sequestration of carbon.

Regarding the environmental impact on the land, although this resource is not actually consumed it suffers anyway huge modification due to the development of hydropower facilities, which are long lasting. This modification and alteration of the land implies net habitat losses. In respect with the fluctuation in the level of the water in reservoirs and river regulation, these can have positive impact on the biota depending on the climate, soil condition and human use (Husebye 2002).

Friedrick & Marheineke (1994) proposed four different quality classes of land, with the aim to track the modification and alterations of this resource.

- *Class I:* natural (human influence since industrial revolution not larger than the influence exerted by other species)
- *Class II:* modified (human influence larger than other species' influence, but mostly uncultivated, e.g. natural forest)
- *Class III:* cultivated (human influence larger than other species' influence, mostly cultivated, e.g. agriculture, forestry)
- *Class IV:* built up (dominated by buildings, roads, dams, mines etc.)In this study is reported that concerning hydropower development the main land change is from class II to class III, a shift induced by the construction of the dam and the filling of the reservoir.. It's important to notice that this study was developed on European study cases, had it been performed in other place as Africa, the main shift would most likely be different

The study performed by Bauer et al. (2007) on several hydroelectric located at Union for the Co-ordination of Production and Transmission of Electricity (UCPTE) countries several hydroelectric. And presents discussion related to environmental socioeconomic impacts that arise from a hydroelectric project. The following environmental impacts are the ones that are not being covered by any environmental indicator and impact assessment currently existing

Climate: An example is the alteration of the local climate because of the increase of humidity, due to the evaporation, whose side effects would vary according to the regional location.

__Geophysical alterations:__ due to modification on the delta formations and possible increase on upper reservoirs of sedimentation of suspended solids causing "silt up". Alteration on the geological stability by inducing seismic activity

__Aquatic:__ disappearing of waterfalls, alteration of the timetable fluctuation of the water end of natural flooding, generation of impair water quality due to changes in the regulation of the water that affects the ground water conditions. Alteration of the water quality can be caused also by other aspect as the residence of water.as well as the aeration level creating anoxic conditions, thermal stratification and generally unhealthy conditions for aquatic life.

__Accident:__ due to dam failure, though in the study case due to being an underground project this accident would have other type of effect, that were not review by (Husebye 2002).

__Impact on Biodiversity:__ Alteration set-up of species and a reduction in species richness, due to a disturbance on the natural environmental. Changes in biodiversity are mainly mediated by habitat alteration. Modifications on watercourses are the main reason for affecting flora and fauna. *(Extension and frequency of flooding, Drought condition below diversion points, Stresses from rapid changes in water level, Water quality in ground water conditions)*

__Impact on humans__: On each of the life cycle stages Thohne & Kallenbach (1988) have associated a health concern: material provision (acute occupation, occupational disease, transport related risks, public disease from pollution), Plant construction (acute occupational), Plant operation (occupational risk, public risk, risk from change in water quality, increased pollution and increase of water-borne diseases.) Water disposal (acute occupational), Dismantling (acute occupational)

__Social and socio-economic impacts:__ this type of project would provide benefits for societies in general, but it always faces public resistance from local communities (not in my back yard phenomenon). Among these impacts there is land inundation, which can cause losses of productive agricultural land or forest, pasture land, resettlements, and fishing restraints (large

Manmade lakes often sustain high and reliable stocks or fish, encouraging development of artisan and sports fishery).

Aesthetic Impact: Visual impact due to the introduction of large reservoir, where waterfalls and other natural water bodies might disappear. The introduction of large water bodies can be positive for the landscape if it's planned carefully.

2.1.6. Regular Environmental Impact Assessments "HydroPeaking Environmental impacts assessments "

2.1.6.1. Environmental impact of pumped storage hydropower plants

(Bakken 2011)

This is a presentation of the current research carried out by the center for environmental design of renewable energy (CEDREN) regarding the biological impact due to the operational phase of the pumped storage hydro plant. The following topics are discussed: the risk consequent to the spreading of species & toxic , the implication at the littoral zone (close to shore max depth 10 m), alteration of the feeding pattern due to modification of invertebrates and zooplankton on the littoral zone , lower visibility due to erosion, fatality of large species through turbine operation. Other impacts studied are related to: Ice formation, water temperature, local climate changes, water quality alteration, modification of fish & invertebrates, alteration of biodiversity and landscape, agricultural and forestry activities.

2.1.6.2. Effect of hydropower peaking flow fluctuations on community structure and feeding guilds of invertebrates colonizing artificial substrates in a large impounded river

(Troelstrup & Hergenrader 1990)

Type of assessment: Comparison on the behavior of invertebrates' communities below a power peaking impounded and flow re-regulating impoundment on the Missouri River USA.

Description of the study, samples were taken of the invertebrates communities located in the shallow part and were evaluated their disturbances subjected from fluctuations; another sample community was from the deeper part under the effects of water fluctuation.

Results, from a statistical of the samples was found that fluctuating discharges had no significance effect on number of taxa or densities on a continually submerged artificial substrates. However, greater number of types and densities of invertebrates' families were observed on deep versus shallow samplers. Other relevant aspect was depending to the two main variables under evaluation (profundity and flow type) the invertebrates vary on their community sizes.

2.1.6.3.Review of Literature related to the Downstream Ecological effects of hydroelectric power generation

(Steele & Smokorowski 2000)

Presents a literature review of the ecological impact associated to the hydroelectric operations. The studies reviewed proposes in stream flow methodologies as historic flow, hydraulic, habitat-based methods, aquatic biota studies, fish microhabitat use, migration, and embryo development. And mitigation actions that are employed in the presents to lessen the effect of hydro generation on aquatic biota and habitat are reviewed too in this study.

Some of the main results and findings review are related to the interdependency of the riverine ecosystems and their environment, where alterations of the flow regimes can the severing of connectivity upon them are the most pervasive influence of humans on river landscapes.. Where an example given of this is how dams cause discontinuity in the longitudinal distribution of physical properties in a river, which in turn impacts on the biological communities that depended on this type of profile.

Other topics review are in relation to the necessity to generate studies based on scale (temporal and spatial) this in order to take into consideration different spaces of the water bodies and their ecosystems, and how their interactions between each other varies due to modifications along time on the river regulation.

Several in-stream flow determination methodologies are being reviewed, where hydraulic methods of in stream flow determination are developed from a relationship between discharge and several in situ specific hydraulic attributes of the river that is assumes to be related to an ecological function.

Another method reviewed is the habitat guilds, where a group of specie that exploits the class of environmental resources in a similar way is compared in against their community behavior when is expose to alterations on the river flow.

Some of the main conclusions from this review are:

- Fish growth is a well-used parameter for measuring response to flow manipulation, though they think that cannot relay totally upon
- Research has focus mainly on salmonids species
- Necessity to consider and evaluated the interdependency of scales (temporal and spatial) variables can affect and modify the ecological response of species

2.1.6.4.Hydroelectric Reservoirs-the Carbon dioxide and methane Emission of a "Carbon Free" Energy Source

(Farre 2007)

This study provides an overview of the GHG generation during the operational phase of reservoirs. It comperes the GHG emissions from the hydropower plat with reservoir against the ones from thermo-power plants. The decomposition of the organic matter on the bottom of the reservoirs is the main factor for the generation of carbon dioxide and methane. Two main pathways that describes how does the GHG arises from water coming from reservoir reaching the atmosphere are being presented; These are: -Water diffusion and bubbling in the reservoir and river downstream, and -Water passing through the turbines.

The overall conclusion of this study is that in some cases hydroelectric reservoirs GHG emission are even higher that the ones from thermo-power plants, this is especially true for the facilities located in the tropics. The main reason behind this is the stratification in the water that is generated by the warm air boosting up the decomposition of organic matter and producing GHG.

2.1.6.5. Environmental aspects of pumped storage development reasons or emotions

(Vetz 1971)

An inherent capacity of the pumped storage hydro plant is considered to be the potential to improve the environment and to enhance the quality of life, providing electricity and potable water.

Here is provided a list of the environment negative impacts followed by the potential benefits. The adverse impacts, considered in a "narrow" ecological sense are:

- Disturbance of large segments of the natural environment
- Appropriation of extensive land areas in reservoir sites
- Groundwater alteration and danger from dams failure
- Change in aquatic biology and damage to fish
- Upset of natural river regime
- Induction of hydro diurnal pulsation in stream flow and reservoir levels
- Alteration of natural science and historical values, including overhead transmission lines

The ecological potential benefits according to Vetz (1971) are:

- Generation of electrical energy relatively close to urban and industrial zones
- Drought control by stream flow augmentation during critical dry (weather) seasons
- Elimination of hydro diurnal pulsation in stream flow

- Flow control by “decapitating” peak flow discharges with large capacity pumping
- Stream water quality enhancement, substantial increase in streak self-purification capacity, lower concentration of residual contaminants trough flow augmentation; control of urban drainage and combined sewer overflow
- Reservoir water quality enhancement obtained by daily pumping cycle, elimination of reservoir stratification, reduction in BOD in long storage, increase of dissolved oxygen approaching saturation levels, temperature of water and control of biological productivity
- Community and industrial raw water supply of good quality.
- Water base recreation including: extensive fishing on downstream off-channel reservoir within easy access from urban high-population areas, riverside recreation and park development in urban areas flow augmentation maintaining river stage during dry weather season

2.1.6.6. Environmental studies for a pumped storage-nuclear station power complex

(Sherlock et al. 1971)

It presents a review of environmental impacts on human environment of a pumped storage nuclear station project, according to both interface technology. The impacts are divided between indirect and direct.

The indirect impacts are mostly related to the hydrology and the water quality alteration:

- Alteration on the aquatic life due to the modification of the flow regime
- Modification of the habitat and feeding areas due to the continuous fluctuation of the impoundment average per day
- Changes in the water quality
- Impact of the new large bodies of water upon the local climate and consequent need for local meteorological studies.

While the direct impacts are:

- Relocation of families
- Change in the aesthetics due to the construction of the facility
- Visual impact on the rural landscape

In addition is introduced a program to validate the expected impact along the operation of the facility. This is necessary due to the incapacity of understanding and estimating the impact beforehand the conclusion of the construction because of time scarcity. The program includes a specific monitoring on:

- Hydrological base
  - Surface water (Dissolved oxygen, temperature, Turbidity, Conductivity, PH)
  - Laboratory analysis of water sample (CO_2 Dissolved oxygen, Total dissolved solids, Alkalinity Hardness Chloride, Sulfate Silica Iron Calcium Magnesium Sodium Phosphate Ammonia Nitrate Nitrite Biochemical Oxygen demand Chemical oxygen demand Mercury)
  - Ground water
- Meteorological base
- Biological base
  - Fish (specie inventory, population composition)
  - Plankton (Quantitative and qualitative analysis, food web relationship indicator per organism)
  - Benthos

2.1.7. Life cycle assessment to energy storage technology

2.1.7.1. Life cycle Environmental assessment of Lithium-Ion and Nickel metal hydride batteries for plug-in hybrid and battery electric vehicles

(Majeau-Bettez et al. 2011)

Type of assessment: Comparative study between three batteries for a plug-in hybrid and a full performance battery for electric vehicles. The batteries being assessed are nickel metal hydride (NiMH), nickel cobalt manganese lithium-ion (NCM), and iron phosphate lithium ion (LFP).

Assumption: energy efficiency of 80% for NiHM and NCM, and 90 % for Li-ion. Lifetime of 3000 cycles and 6000 cycles

System Description: Covers the whole production chain and the use phase. The end of life phase is not covered mainly because the recycling of this type of batteries is not yet widely implemented (as there is no beneficial secondary metal production reuse during the manufacturing of the battery).

Type of use: the functional unit investigated is 50MJ, that the author calls a charge-discharge approach.

Environmental impacts: Midpoint indicators evaluated are from (ReCIpe) method
Data: the inventory is linked to Ecoinvent v2,2 as background data system, Average European conditions are assumed in most of the case. Infrastructure and transport requirements are included.
Conclusion & Results: the NiHM battery performance is significantly worse compared to the two other batteries. This is related with the use phases and the differences on the efficiency, Li-ion battery is expected to store on average 2,5 time more energy during the whole operational lifetime than the NiHM. Regarding all the three batteries the manufacture energy requirement is the category with major GWP.

Table 4 Main results of LCIA performed to batteries

Fu: Charge-discharge 50MJ		NiMH	NCM	LFP
Global warming potential	*kg CO2-eq*	3.5	1.9	1.4
Fossil Depletion	*kg oil-eq*	0.99	0.45	0.37
Ozone depletion	*CFC-11-eq*	1-E 05	1,1-E 05	7,5-E 60

2.1.8. Life-cycle assessment of electricity generation options: The status of research in year 2001

(Gagnon et al. 2002)

Type of assessment: Environmental impact of electricity generation system, based on life-cycle assessment. The environmental performance of several electricity generation options that produces for different demand components of the electricity load are benchmarked. The ones that are highlighted are nuclear power, and hydropower for the base demand components, and solar and wind for the peak demand component. Beside this is provided a good description of the main impact categories that are evaluated.
System description: there is no much information provided in relation to the description of the systems that are used for developing the assessment, though is important to note that Gagnon, and Uchiyama have produce several impact

assessment for different electricity generation options (Uchiyama 2007; Cagnon & Chamberland 1993; Gagnon & Vate 1997)

Environmental impacts: The main environmental impacts that are evaluated in this assessment are presented in the next table

Table 5 Introduction & Description of the main environmental impacts that are suggested by this study to be evaluated to hydropower plant facilities

Issue	Type of impact	Precursor pollution and main sources
***Acid rain:* formation of sulfuric and nitric acid**[10]	Regional impacts on lakes, forest and material	SO_2 sulfur dioxide, from smelters combustion of coal or oil, and from processing of natural gas
***Photochemical smog:* formation of ozone and other toxic pollutants in the lower atmosphere**	Affects human health at local and regional level Reduces productivity of agriculture	NO_x nitrogen oxides, from transportation (mainly) or any combustion VOC_x volatile organic compounds, from transportation, refineries, oil and wood heating
Greenhouse gases	Climate change affecting agricultural and forest productivity, and increasing the likelihood of extreme events such as hurricanes, floods and droughts	CO_2 carbon dioxide, from fossil fuels combustion and destruction of forest. CH4 methane, from livestock, paddy fields, landfills sites, extraction, transportation and distributions of natural gas, extraction of oil and coal

Results and Comments: the following table presents the results for the GHG emissions and the direct land requirement per electric generation assed.

[10] *All the information has been taken from (Cagnon et al, 2002)*

Table 6 Main results obtained along the benchmarked performed to generating technologies

	Base load	Base & Middle load			Inttermitent load	
Impact indicator	Hydro with reservoir	Hydro run of river	Nuclear	Biomass	Wind power	Solar power
GHG (kt CO2 eq./TWh)	15	2	15	116	9	13
Direct land requierment (Km2/TWh)	152	1	0.5	553	72	45
Energy pay back ratio (energy output/energy input)	205	267	16	5	80	9

[11]

The hydropower run of river plant has the best performance regarding GHG emissions generation followed by reservoir plant. Both of them are the best options for providing energy at base load and peak loads requirements, while wind power is the best concerning peak load, or what is presented as intermittent options. This is excluding nuclear power plant performance, mainly because de commissioning of the fuel was not considered. These results can provide a hint of how the interaction between a pumped storage hydro plant and a wind power could enhance the service capacity for renewable sources as wind and solar, while replacing the need for natural gas power plant or any fossil fuel running power plants in order to provide middle and even why not base electricity demand.

In relation to the direct land use requirements all the renewable generation production technologies have the highest demand for land use transformation, being the hydropower with reservoir the one that scores with the highest fallowed by wind and solar, though the exception is run of river hydropower. This indicator tells us about the amount of land being transformed in order to build up and operate a certain plant. Biomass plantation has the worst score.

Another relevant aspect is that the land requirement for hydropower plants with reservoir is dependent on site-specific condition. This makes that the results could

[11] *The result shown in the table have been taken from (Gagnon et al. 2002)*

dramatically change according to the plant that is being assessed. Would be interesting to measure the indirect land requirement where by indirect requirements would be understood as the sum up of the land employed along the value chain of a specific technology would be score, although it could be not as large as the direct ones.

Gagnon et al.(2002) proposed an energy payback ratio indicator, which provides information regarding the energy produce during the whole life span of the facility per the total energy required to build, maintain and fuel the generation equipment. Providing the amount of actual energy produce in relation to the amount being require so that energy can be produce, in this sense when the ratio is close to 1 is because it requires the same. Over one is because its output is superior to the input of energy required. In the case of Hydro it has the superior performance being run of the best. Though to this is important to acknowledge the uncertainty of the possible scarcity on water resources at the location of the plant.

3. Life Cycle Assessment Methodological framework

Life cycle Assessment is a systemic approach that allows evaluating the environmental performance through the life cycle of a product system. This evaluation is performed by the characterization of several environmental impact categories. This approach states that the environmental impact has a wider scope than being just related to a single location or service, but rather it occurs along all the life cycle of products and services.

By life cycle is meant all the steps happening from the extraction of the raw materials, passing through the process and use until the end of life of the product. The possibility of tracking the several transformations of a single product along a complex and intertwined chain of processes makes it a system tool well suited for environmental decision making. LCA is what can be viewed as a quantitative approach and a holistic perspective that is capable to provide information on how modifications of the system under scope can generate co-benefit or trade off in the whole system.

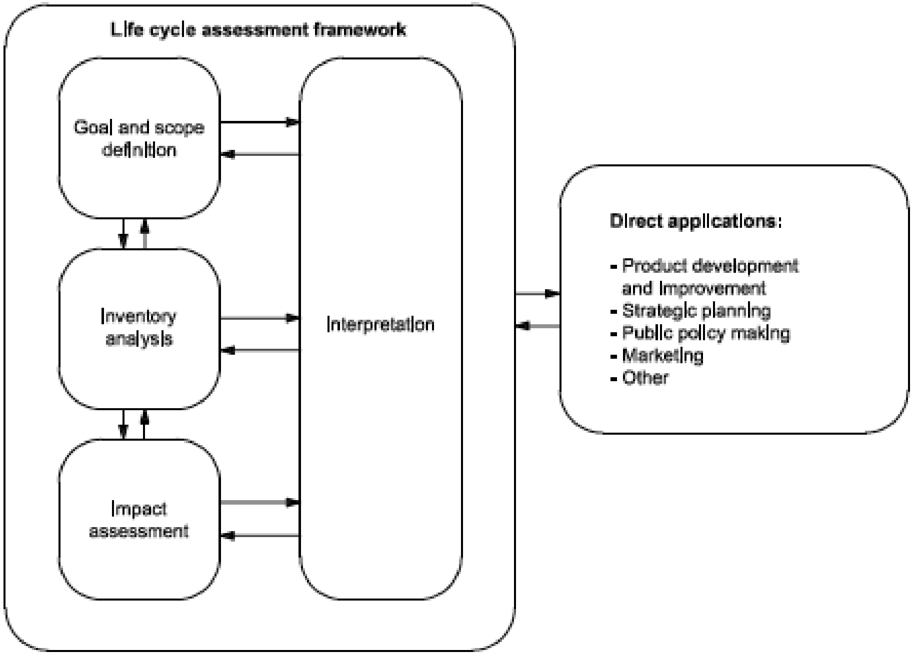


Figure 2 General description of the life cycle framework (ISO 2006a)

The life cycle assessment addresses the environmental impacts of a product system, in order to evaluated and compare different technological product systems (ISO 2006a). This framework has been standardized by the international Organization for standardization under the 14000 family standards. LCA has an environmental focus, is a relative and iterative approach, where transparency is important. It is relative in the sense that is structured around functional units; each defining what is being studied.

The LCA studies include four consecutive and iterative main stages (figure 12) : Goal and Scope definition, Inventory Analysis, Impact Assessment and Interpretation.

3.1. Goal and Scope definition

The aim of this first stage is to provide a description of the assessment carried out, while defining who would be the intended audience for it. In this stage the functional unit must be defined and presented clearly, mainly because it defines the quantification of the identified function (performance characteristic) of the product. In this way the functional unit provides a reference to which the inputs and output are related. Moreover the functional unit can be taken as a reference providing the possibility of the LCA results to be benchmarked. This stage well defines the data requirements, assumption and limitations the study presents.

Is in this stage where the system boundaries are defined, in order to describe the key elements of the system; ideally the way of modeling should be such that the inputs and the outputs at its boundaries are elementary flows. Other aspects to be considered are:

- *Distribution & transportation*
- *Production and use of fuels, electricity and heat*
- *Use and maintenance of product*
- *Disposal of process wastes and products*
- *Additional operations, such as lighting and heating.*

3.2. Inventory Analysis

This stage involves the data collection and further calculation of relevant inputs and outputs or an inventory that describes the systems under assessment. The data required for each process within the system boundary is classified under the following major headings (ISO 2006a)

- Energy inputs, raw materials inputs, ancillary input, other physical inputs
- Product, co-product and waste
- Emission to air, discharge to water and soil
- Other environmental aspects.

This stage is generally time consuming and during the consolidation of the data there might appear new data requirement or limitations might be identified, making this stage iterative and crucial for the further one.

It is important to highlight that the data calculation and flows allocation are the main factors that would provide validity to the impact assessment. Regarding to this assessment the core focus has been on the underground construction process, where a meticulous calculations and further development upon the construction of the inventory has been considered. Concerning the other foreground stages, due to limitation on primary and secondary sources of data, the inventory has been more general, the only exception has been the transformer in whose case it has been use the inventory collected in other study (Raquel 2011)

With relation to the data collection at the underground construction process, due to the lack of existing background LCI databases Ecoinvent v. 2.2 (2008) at tunneling process several assumptions has been made. The same has happened in relation to several materials required for the construction of the reversible Francis turbine and spoil tip.

3.3. Impact Assessment

This step is about evaluating the inventory data gathered according to the environmental impact categories; is this stage that is addressed as the Life Cycle Impact Assessment. Its objective is to assess the significance of potential environmental impacts according to the LCI and to be carried out it needs a selection of impact categories, further classification and a characterization of the impacts associated to the LCI

3.3.1. Impact Categories

For coming up with the assessment has been employed the hierarchist version from the Recipe midpoint Method, which has 18 different midpoint impact categories, and 3 different regarding realities (Goedkoop et al. 2009)

The Hierarchist perspective has been chosen because it has a coherent time frame, which is usually or at least ideally used for considering the effect of policy principles (time frame is of 100 years). The other two perspectives that Recipe method proposes are the Individualist and the Egalitarian, the first has a short span of time, which is inherent to a technological optimisms regarding the capacity of dismantling emission in a very short run, the latter is based on the precautionary principle, considering a very long time frame of 500 years, regarding the impacts of global environmental impact indicators (Goedkoop et al. 2009).

The environmental midpoint impact categories that have been chosen to be reported are presented in the following list. These are the categories that have been found to be evaluated in reviewed environmental assessments of hydropower plant (Dones et al. 2007; Gagnon & Uchiyama 2002; Gagnon & Vate 1997; Statkraft & Ostfold 2006; Varun et al. 2010; Vold et al. 1996; Bauer et al. 2007; Husebye 2002)

Table 7 Environmental Impact categories ReCipe that evaluated the overall performance of the pumped storage hydropower plant

Impact Categories (ReCipe)		Unit	Description
CC	Climate Change	*kg CO2-Eq*	Contribution emission to greenhouse effect
FD	Fossil depletion	*kg oil-Eq*	Contribution to depletion of hydrocarbons resources
HT	human toxicity	*kg 1,4-DCB-Eq*	Risk associated to human health
MD	metal depletion	*kg Fe-Eq*	Contribution to depletion of mineral resources due to extraction
POF	photochemical oxidant formatior	*kg NMVOC*	ground level ozone production
WD	water depletion	*m3*	Extraction and transportation of water resources
PMF	particular matter formation	*kg PM10-Eq*	Particles generated due to combustion of fossil fuel
TA	terrestial acidification	*kg SO2-Eq*	Acidifying gases that might dissolve in water causing acid rain
NLT	natural land transformation	*m2*	Transformation of natural land
ALT	agricultural land transformation	*m2a*	Transformation of natural land into productive land
ULO	urban land occupation	*m2a*	Transformation of productive land into urban land

3.3.1.1. Greenhouse gases emissions

The Intergovernmental Panel on Climate Change has produced a *Summary for policymakers* on the impacts of climate change (IPCC 2007). It considers the following impacts as "likely" or "very likely" to happen; Godish (1997) listed them:

- "More intense precipitation events: Increased floods, landslide, avalanche, and mudslide damages"
- "Increased summer drying over most mid-latitude continental interiors and associated risk of drought"
- "Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities"
- "Intensified droughts and floods associated with El Nino events in many different regions"
- "Sea-level rise and an increase in the intensity of tropical cyclones would displace tens of millions of people in low-lying coastal areas of temperate and tropical Asia"

Following the increased relevance of anthropogenic emissions in relation with climate change, scientific community has focused during the last decades to assess this type of emission. Most of the studies produced so far employed the concept of "CO_2 equivalents", for assessing the results obtain trough theirs investigations. The concept of "CO2 equivalents" includes CO2 and GHG. The IPCC has proposed a set of global warming potential indicators is calculated in relation to CO2. These indicators allows converting any GHG into CO2 equivalent, as an example 1 gram of methane has a global warming potential of 21 in comparison with one gram of dioxide carbon (Houghton 2009)

Greenhouse gases emission and pumped hydro storage facilities

The GHG emissions from this type of energy system have been associated to the upstream production process of materials employed during the construction phase (Bauer et al. 2007) and to the operation phase, being in this case strictly dependent on climate specific conditions (Schuller & Albrecht 2008)

Several relevant issues related to hydropower facilities and GHG emission occurs at the reservoir due to the amount of flooded biomass. In the case of Norway and the Tonstad III , located in boreal climate conditions, according to (Gagnon et al. 2002; Schuller & Albrecht 2008) the decay amount of flooded biomass should be depreciable., but If the facility was located in a tropical area this factor would have been relevant (Farre 2007; Husebye 2002)

Another interesting aspect concerning the pumped storage hydro plant is the operation at the pumping mode, which varies depending on the source of the energy being use to run this mode. This aspect is further developed during the life cycle impact assessment.

3.3.1.2.Land use transformation

In the near future the amount of acres of land required for developing or expanding an existing energetic project it's expected to become more and more relevant. This is mainly related to the present population growth dynamics and the direct and indirect implication of this population explosion. Among the direct impacts there is the increase of the demand for more energy, new land for cities, industries and for food production. Moreover the current de-carbonization trend of the energy system, with the construction of intermittent renewable sources plant (wind and solar) requires the use of new terrains, while alternative bio-fuels are consuming crops traditionally used for food production. As a consequence the land is actually turning into a scarce resource (Cagnon & Chamberland 1993; Dubreuil et al. 2006)

A robust description of the impacts related to the land use can also illustrate how the land quality can be modified by several others impact categories that are usually measured when a LCIA is performed: acidification, eutrophication, toxicity, biotic resource depletion (Dubreuil et al. 2006).

At the same time (Dubreuil et al. 2006) points out some aspects related to land quality changes that the traditional LCIA doesn't consider. These are: biodiversity losses jeopardizing biotic natural key elements that support ecosystem services; impacts on ecological soil quality influencing nutrients cycles.

In the case of pumped storage hydro plant, the transformation of forestland into aquatic system is an example of the environmental issue behind land requirement (Cagnon & Chamberland 1993; Friedrick & Marheineke 1994). Gagnon et al. (2002) proposes a performance metric indicator, the "energy payback ratio", defined as "the ratio of energy produced during a generation equipment normal life span, divided by the energy required building, maintaining, and fueling it." If a system has a low payback ratio, it means that much of the energy is required to maintain it; this most surely implies that it is likely to produce a lot of environmental impacts. In the case of renewable energy this can be translated into the impacts occurring at building facilities. Gagnon et al. (2002) suggested that Nuclear power has the overall lowest land requirement if the waste disposal is not considered. Regarding hydropower, while it has high land requirements, even higher than wind power and photovoltaic solar panels, at the same time it is the only one among the three energy sources which is capable of providing Base and peak load energy services.

Friedrick & Marheineke (1994), propose to evaluate the land transformation under four main categories, according to the change or alteration suffered. In the case of hydropower plants most of the alterations occurred are from type II to type III, implying a conversion of uncultivated and natural forest into cultivated land.

3.3.1.3.Acid Precipitations

Environmental issues: The most important aerosols from anthropogenic sources are the sultanate particles, which are formed from the chemical sulfur dioxide gas – emitted in large amount by power station and gas and oil industries. The concentration of sulfate particles influences in a short term the "acid rain" pollution, which is mainly cause by SO_2.

“Acid rain” usually leads to the degradation of the forest and fish stocks. The vulnerability of forest varies significantly according to the type of soil involved, in this sense it would be challenging to establish a direct connection between atmospheric emission and ecosystem impact.

Among the several indirect impacts of atmospheric emission of SO_2 and NO_x Godish (1997) suggests the ones listed below:

- Acid tends to remove some essential nutrients from soils (K, Ca, Mg).
- Acid may mobilize toxic metals such as aluminum, which can damage roots.
- Adding nitrogen, the main nutrient of plants, may create an unbalance in resources and make trees more vulnerable to diseases and frost. Impacts of other atmospheric pollution must be also considered.
- Photochemical smog can damage the leaves.
- Climate change may increase heat stress or intensity of droughts.

Main findings concerning acid precipitation:

- Emission factors of hydropower and nuclear energy are hundreds of times less than those from coal-based power generation systems without scrubbing. Considering SO_2 and NO_x, coal, oil and diesel based generation systems are important contributors to acid precipitation.
- Biomass has a low emissions factor for SO_2 but a very high factor for NO_x. It is therefore a significant source of acid precipitation.
- Natural gas, when considering the processing of fuel and NO_x emissions, can also be a significant source of acid precipitation.

Expectations: Some of the benefits of wind power (intermittent) are dependent on the network conditions and more difficult to assess. Generally speaking as wind power reduces the use of oil-fired plants, this would lead to a reduction of net emissions; however, in some cases, the use of wind power may increase the number of oil-fired plants (used as backup). On the contrary the introduction of energy storage technology would probably help to reduce the acidification of the land if the type of energy stored is from renewable sources as wind.

3.3.2. Classification & Characterization

The classification stage consists in sorting out the inventory data according to the environmental impacts they contribute. The emission of NOx and NH3 for example contributes to the eutrophication potential (Baumann 2004).

The characterization consists in calculating, utilizing scientific models, the relative contribution of the emission and resource consumption to each environmental impact category.

3.3.3. Interpretation

In this phase is presented the entire finding of the impact assessment. The result shall be consistent with the goal and the scope of the study, providing an explanation of the limits of the model and some recommendations for further studies (ISO 2006a).

4. System Description

This chapter introduces the system under assessment and its boundaries. First is provided a description of the case of study, then it follows the presentation of the functional unit and the boundaries of the system evaluated, a description of the system's components, the assumption taken for completing the inventory and the estimation of the major mass flows of the system. At the end is given the inventory data and a review of the quality of the data.

4.1. Tonstad III as case study

Sira-Kvina is a leading company producing renewable energy, with a total annual production of 6,300 GWh, which is equivalent to 5% of Norway´s electricity production is on a design and evaluation process for an additional installation of a pumped storage hydro plant at Tonstad, with the aim of pursuing a better utilization of the water potential, while improving the regulation of the electricity prices in a short, medium run. Sira-Kvina envisions the possibility of the development of cable connection to foreign countries, and the further development of renewable energy facilities as wind farms onshore and offshore, (Sira-Kvina 2007).

Tonstad III pumped storage plant would be located in the municipality Vest-Agder at Sirdal, in the Sira river that is connected with Sirdal Lake and Homstøl Lake. The present power plants installation at Sira-Kvina is an intermingled connection between several lakes, rivers and reservoirs, with the total of eight hydropower plants (each with several turbines). The overall capacity of this complex is of six billions kWh (6TWh)), equivalent to a 5% of Norway's electricity production.

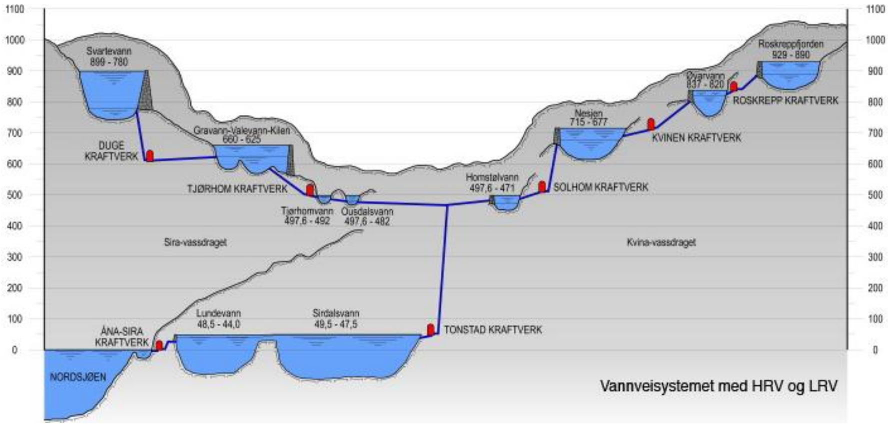


Figure 3 Overview of the existing power plants and waterways at (Sira-Kvina 2001)

4.1.1. Technical description

The new project development would be constructed at Tonstad, where already exists a complex with four hydropower stations, with an install capacity of 960 MW. This new installation would have a capacity of 960 MW split into two units with the novelty of a pump integrated in the equipment. Water resources would be provided by a new underground tunnel connecting Homstøl lake and Sirdal lake, 12,5 km long (Sira-Kvina 2007).

It won't be necessary to further develop the road system; the construction period is estimated to be 3 years the development of Tonstad III power station with pumping mode possibility (Sira-Kvina 2007)

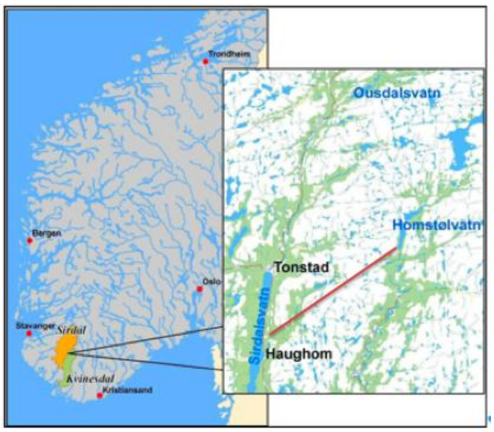


Figure 4 Spatial location of the Construction of Tonstad III (Sira-Kvina 2007)

The underground facilities include tunnels associated to mechanical structure, generators, turbines and transformers.

The headrace and tailrace of the tunnel would have a cross section of 120 m2.

The pressure shaft will be steel lined. It is expected to blast a total of 1,5 million m3 of muck that would be located at the existing spoilt tips in the upper and lower regions. The reservoirs would be the existing lakes, Sirdal and Homstøl, so they won't be taken into consideration in this assessment (Sira-Kvina 2007).

The electro-mechanical units are Francis reversible turbine of 480 MW each, with an intake capacity of 125 m3 and a pump capacity of 100 m3/s. In the document of Technical specification is presented the possibility of improving the pump mode of the turbine by introducing an Adjustable Speed Drive (ADS). The benefit of installing it would be reflected on an improvement of 1% efficiency of the pumping mode of the units (Walseth 2011; Sira-Kvina 2007)

4.2. Functional Unit and System definition

Pumped storage hydro plant is a mature technology that has been used for storing extra energy capacity in the form of potential energy for over a century. Nowadays as a consequence of a continuously pursuit for energy security, and an increasing boost on renewable energy sources as a strategy against climate change, the need for energy storage has come to attention as a determinant factor for shifting from the actual fossil fuel dependent energy system towards a more sustainable one.

In the dismantling process of GHG emissions, energy storage has gained attention as a facilitator to support renewable energy sources. In this context there are two different systems that would be interesting to analyze: the whole life cycle of a pumped storage hydro plant following a cradle to grave approach, and the life cycle from the required upgrade of an existing hydropower facility into a pumped storage. In the assessment performed, the second option is evaluated, without considering the reservoirs as part of the system, mainly because the study is based on the ongoing project run by Sira-Kvina.

4.2.1. Functional Unit

The system under assessment is highly dependent on the operational phase; the functional unit for this study has been predefined as an amount of energy stored along a period of time. It is express as

$Functinoal\ Unit = 1\ Mega\ Joule\ *\ 1\ day.$ This resembles the operational regime that the pumped storage hydro plant will be working on (Sira-Kvina 2007). This regime has two main aspects; the first is the possibility of storing extra production capacity (regulatory services for any type of electricity source production) during low demand hours, and producing back the electricity during peak hours in a daily basis. This operational mechanism is highly dependent upon the electricity market. And the second, more interesting for this study, is the possibility of enhancing the renewable share at the grid by storing the extra capacity of energy from renewable sources as wind or solar, and introducing it back to the market at peak hours. Uchiyama (2007) records that the average quota of energy produced by wind plant entering to the grid is 20% of the total capacity produced; the rest 80% is lost. Enhancing the amount of renewable energy that can be stored and re-introduced, would make it possible to replace electricity from carbon intensive sources, reducing the carbon intensity of the electricity deliver to consumers and contributing to the dismantling the carbon intensity.

The selected functional unit is 1MJ stored during one Day and it indicates the amount of energy stored during a time unit. It is a charge and discharge(c-d) approach based on an amount of time , making intuitive how the pumped storage hydro plant facility would provide electricity during Peak hours and ancillary services if required. This set up of the functional unit allows exposing the potential savings of GHG emissions and other potential emissions according to the production source of the energy utilized in the plant to run up the pumping mode and the following storing mode.

Pumped storage hydro plant provides the possibility of storing the extra amount of energy produced by renewable sources as wind and solar power, during a predefined amount of time, providing so ancillary services to those types of intermittent systems. This entails the possibility of a future technology transition towards a lower carbon energy system, regarding not only the conventional peak energy demand component usually provided by gas turbine, oil thermal power furnaces, but also the middle demand component of energy normally produced by coal fire thermal power, nuclear.

Table 8 Description of the demand components of the electricity and it generating sources (TEPCO. 2011)

Demand component	Characteristics	Operational requirements	Power source
Peak	-Sharp fluctuation -Short operation duration	-Load adjustment capabilities -Frequent start/stop capability	-Pumped Storage/Gas turbine -Oil /LNG thermal power
Middle	-Large fluctuation -Relative long operation duration	-Relative high frequency capability of activation deactivation	-Oil /LNG thermal power -Coal fire thermal
Base	-Negligible fluctuation -Non-stop power generation	-24 h operation	-Run-of-river hydropower -Nuclear -Biomass
	-Intermittent system (no flexible) -Need a backup production	-Need a backup system with immediate response	-Wind power -Solar photovoltaic[12]

4.2.2. Pumped Storage Hydro System (life cycle stages)

Here are reviewed in detail the main components of the system, the data and the assumption made in order to compile the LCA. Neither in the literature reviewed nor in the interviews held with experts was found any record of LCIA evaluating underground construction and Francis Turbines. Regarding the dismantling phase it

[12] *Energy demand component presented by TEPCO*

has been modeled only considering the materials and parts that are made from metals.

The table below presents the principal stages that have been considered for the assessment: 1.the operation of the plant, 2.the construction, 3.the dismantling.

Table 9 Description of the set up at the pumped storage life cycle inventory

Table (Foreground System): Pumped Storage Hydro Plant		
Operation	MJ*day	1
Construction	Unit	3,9637E-13
Dismantle	Unit	3,9637E-13
Underground	Unit	0
Reversible Francis Turbine	Unit	0
Spoil Tip	Unit	0
Transformer	Unit	0
Electricity Production mode	(M J//kWh)*day	1
Energy lost ŋ	(M J//kWh)*day	0,276
Maintenance	Unit	0

The operation phase includes the functioning of the power plant, the allocation of the lost energy as a proof of the efficiency inherent to this technology, and the maintenance (replacement) of part of the reversible turbine and transformer. Another element considered at this stage is the load factor that distributes linearly as total output from the operation phase along with the construction and the dismantling phase.

The load factor distributes linearly on each unit output, being for this assessment the defined functional unit (1MJ*day). The Calculation of the environmental load associated with the construction and the dismantling process of the Pumped storage hydro plant facility is presented at Appendix A. The annual production set of µyear is 365 MJ*day, and the life time of the pumped storage plant of Ʈlife is 100 years

The construction phase analysis includes: the construction process of the underground facilities, the materials of the reversible Francis turbine, the soil tip adequation filling and further restoration and the transformer materials. At the dismantling stage is considered the recollection of metal parts and further recycle process.

The layout of the life cycle phases of the system assessed is illustrated in the figure below. The construction and dismantling phases are taken into consideration along with the operational phase.

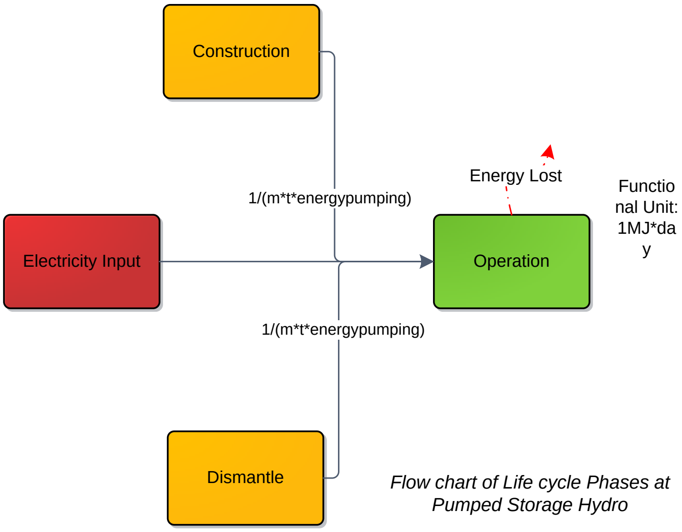


Figure 5 Layout of the life cycle phases of the pumped storage hydro system assessed (introduction of the load factor)

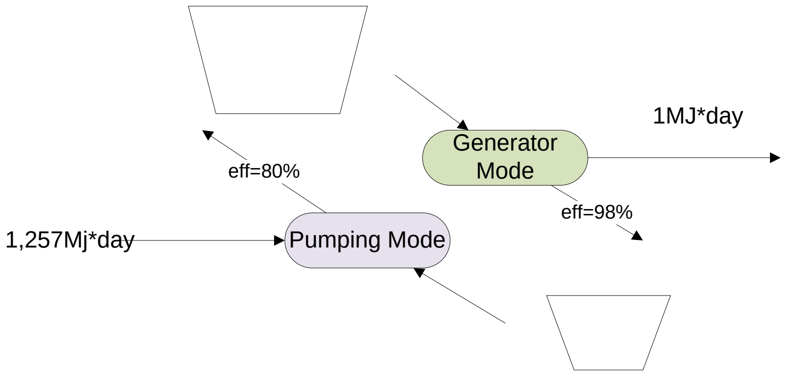
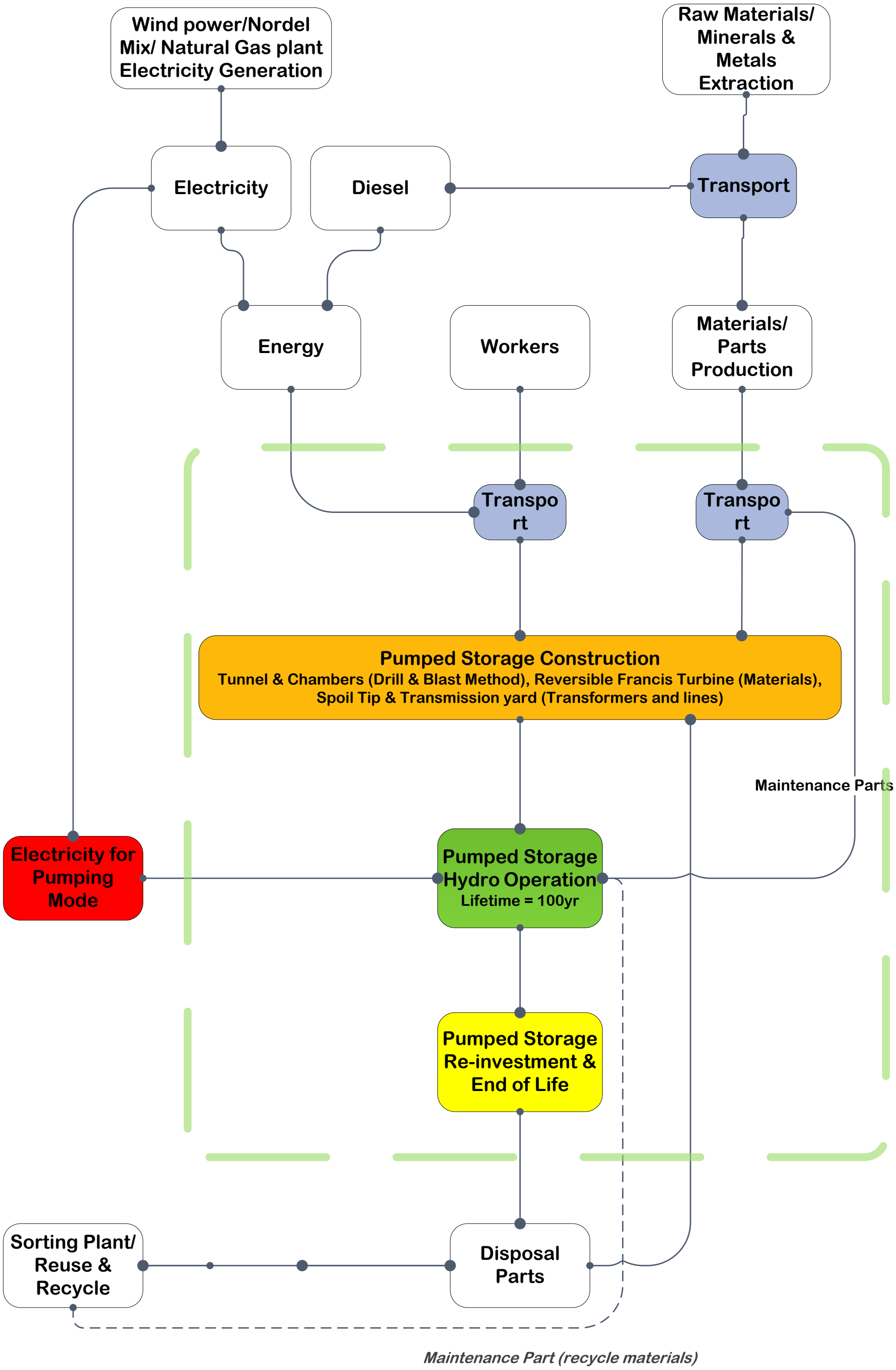


Figure 6 Layout of the operation phase of the facility (overall efficiency of 78%)

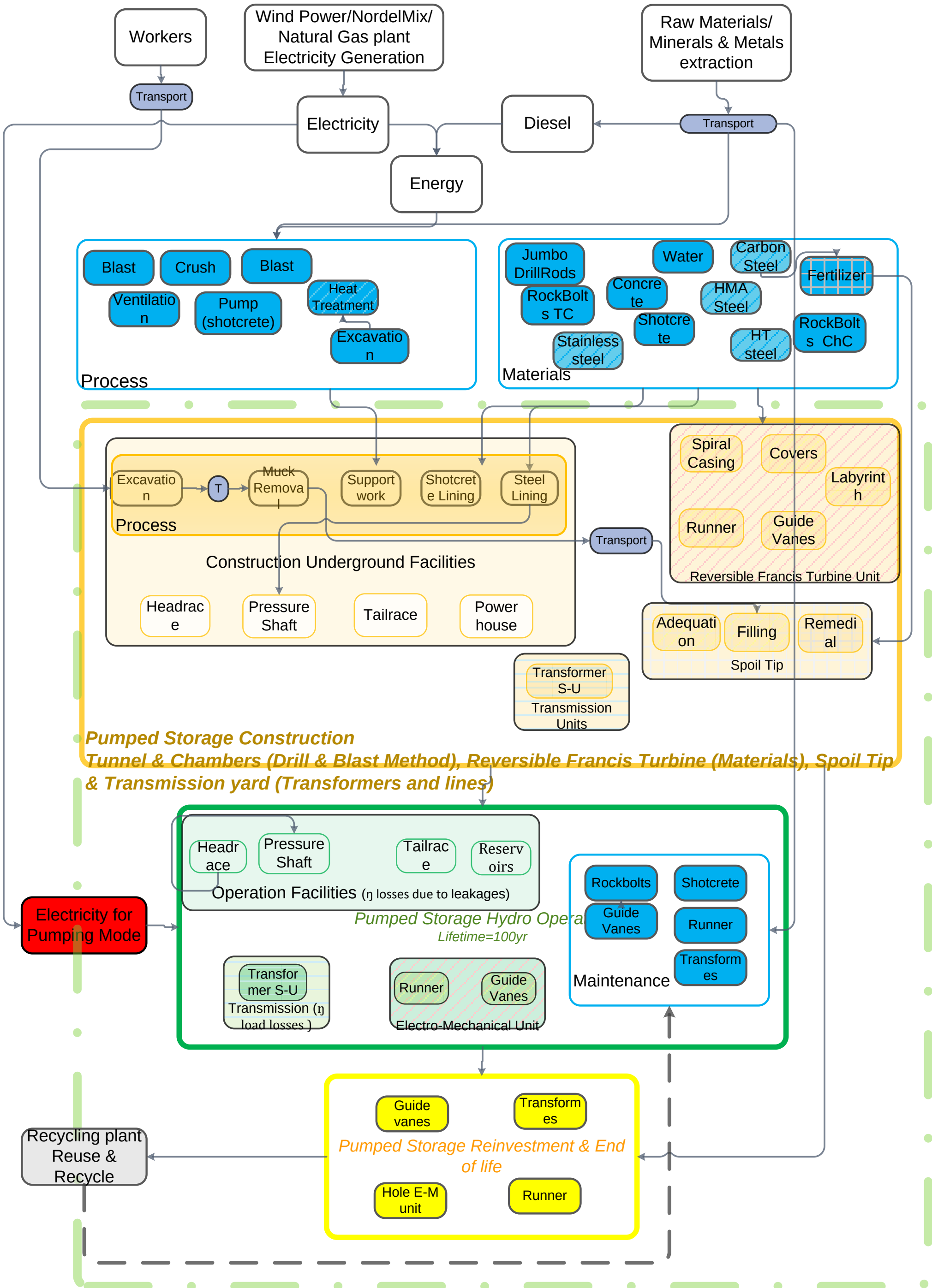
System boundaries

In the following two pages are presented two sketches of the system: firstly one providing a general overview, and then more detail one where is possible to observe which process and resources are employed at each phase.


Wind power/Nordel Mix/ Natural Gas plant Electricity Generation
Raw Materials/ Minerals & Metals Extraction
Electricity
Diesel
Transport
Energy
Workers
Materials/ Parts Production
Transpo rt
Transpo rt
Pumped Storage Construction
Tunnel & Chambers (Drill & Blast Method), Reversible Francis Turbine (Materials), Spoil Tip & Transmission yard (Transformers and lines)
Maintenance Parts
Electricity for Pumping Mode
Pumped Storage Hydro Operation
Lifetime = 100yr
Pumped Storage Re-investment & End of Life
Sorting Plant/ Reuse & Recycle
Disposal Parts
Maintenance Part (recycle materials)

13

13


Workers
Wind Power/NordelMix/ Natural Gas plant Electricity Generation
Raw Materials/ Minerals & Metals extraction
Transport
Electricity
Diesel
Transport
Energy
Blast
Crush
Blast
Ventilation
Pump (shotcrete)
Heat Treatment
Excavation
Process
Jumbo DrillRods
Water
Carbon Steel
Fertilizer
RockBolts TC
Concrete
HMA Steel
Shotcrete
Stainless steel
HT steel
RockBolts ChC
Materials
Excavation
T
Muck Removal
Support work
Shotcrete Lining
Steel Lining
Process
Construction Underground Facilities
Headrace
Pressure Shaft
Tailrace
Power house
Transport
Spiral Casing
Covers
Labyrinth
Runner
Guide Vanes
Reversible Francis Turbine Unit
Adequation
Filling
Remedial
Spoil Tip
Transformer S-U
Transmission Units
Pumped Storage Construction
Tunnel & Chambers (Drill & Blast Method), Reversible Francis Turbine (Materials), Spoil Tip & Transmission yard (Transformers and lines)
Headrace
Pressure Shaft
Tailrace
Reservoirs
Operation Facilities (η losses due to leakages)
Pumped Storage Hydro Opera
Lifetime=100yr
Electricity for Pumping Mode
Transformer S-U
Transmission (η load losses)
Runner
Guide Vanes
Electro-Mechanical Unit
Rockbolts
Shotcrete
Guide Vanes
Runner
Transformes
Maintenance
Guide vanes
Transformes
Pumped Storage Reinvestment & End of life
Hole E-M unit
Runner
Recycling plant Reuse & Recycle

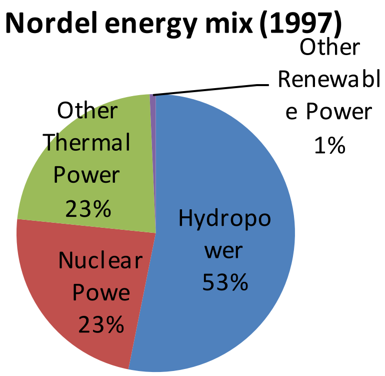
14

14

4.2.3. Operation Phase

The operation phases has been established to be a 100 years. The operational regime of the pumped storage plant is given by the alternation between the pumping mode and the electricity generation mode. In this process there are energy losses due to the efficiencies, the overall efficiency of the reversible Francis turbine in this study is assumed to be 78%. During the Pumping stage the efficiency of the reversible unit is assumed to be 80%, while the generator mode efficiency is assumed to be 98%. This is an in approximate value according to the ones reviewed by H. Chen (1993) who consideres the losses in relation to the efficiency of the water conductors, turbine/pump, generator and transformer, the lowest being of 75,15% and the highest 80,12% (Table 2) There is the possibility of an increase of the overall efficiency around 1%, through the installation of an adjustable speed drive generator instead of a generic one (Sira-Kvina 2007).

[15]During the operational phase of the pumped storage hydro plant, according to the functional unit defined, three potential sources of electricity for running the pumping mode at the pumped storage hydropower plant have been compared. These are: gas turbines, Wind turbines, and Nordel electricity mix. This comparison allows benchmarking the environmental loads related to the energy source stored at the facility, focusing specifically on GHG production..



In order to allocate the environmental impact assessment related to the loss of energy during a pumped storage hydro plant cycle of the pre-set functional unit, a

[15] *Breakdown of the Nordel energy mix*

dummy process has been defined at the foreground process. The amount of energy lost is of 0,257 MJ *day, the calculation for the energy lost due to the efficiency is presented at Appendix A

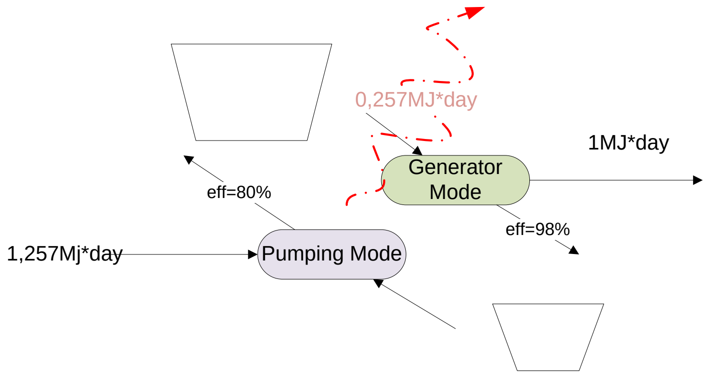


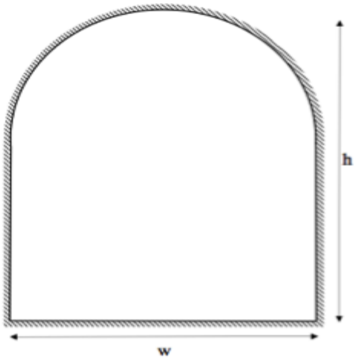
Figure 7 Detail Layout of the operational scheme at the plant, including the efficiency of it.

4.2.4. Construction Phase

For this case study (that is based upon a construction plan), the description of the project is based on the Information provided by the Center for Design of Renewable Energy (CEDREN), while the description of the operations at the construction stage has been obtained partly from literature review and from interviewing experts. Interviews were held with the aim of gathering data for/about the construction of the tunnel (Panthi 2011), and the reversible Francis turbine (Dahlhaug 2011; Walseth 2011). The information obtained to set up the inventory (for the tunnel and the turbine) is the result of years of experience in this topic. In respect with the spoil tip most of the data used are assumptions, while regarding the transformer, the LCI data have been gently provided by Raquel Jorge.

4.2.4.1. Underground Facilities

Figure 8 Normal set up of a water tunnel construction



The underground facilities at the Tonstad III project consist of a headrace, pressure shaft, tailrace, access tunnel, and power chamber. Due to data requirements the headrace, tailrace, pressure shaft have been the only components modeled.

In water tunnels the transmission capacity depends directly in the size and shape of the cross section (Zare 2007),in the Case of Tonstad III the cross section planned for the headrace/tailrace is of 120 m2 (Sira-Kvina 2007). Another important aspect is that the tunnel would be mostly unlined (Broch 2010), beside the pressure shaft that has to be steel lined (Sira-Kvina 2007).

A typical drill and blast water tunnel cross section is presented, where the height to width ratio is assumed to be $\frac{Height}{Weight}$, this implies that the size of the cross section is medium size. The height and the weight of the tunnel at Tonstad III is (of) 11,35 m (cross section is (of) 120 m2). For this ratio has been assumed a value of one order to simplify the calculation of muck removal during the drill & blast process.

Follows the description of tunneling process and the presentation of the inventory

4.2.4.1.1. Drill & Blast method

The heading of tunnel involves several actions; in the figure below the cycle of these actions is presented. In Norway the most often employed method is the Drill and Blast method (DB), mainly due to the earth rock condition inherent to the region (Panthi 2011). Following is a description of each stage, followed by the information utilized for the consolidation of the life cycle inventory.

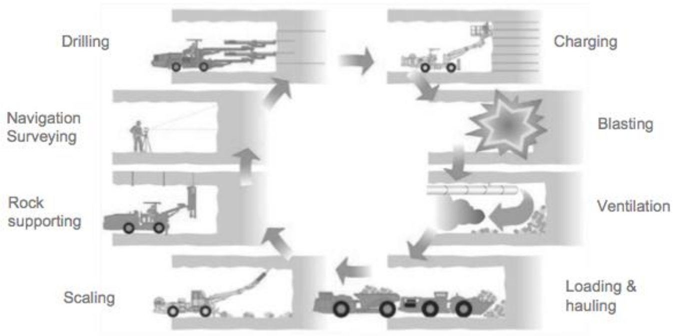


Figure 9 Drill and Blast tunneling cycle (Sandvik Tamrock Corp 1999)

Drilling and blasting is known as the conventional rock tunneling method and is still one of the most common (Dimitrios 2008). DB is an intermittent method due to the way it operates; first several holes are drilled, afterwards each hole is charged with suitable explosives. A standard DB cycle is conformed by a first drilling round, during which several holes (their amount varies depending on the cross section, rock type and dynamite employed) are performed, this in order to generate several V-cut[16] that would allow to obtain a predetermined contour after the blasting round. Often these holes are perforated mechanically by employing drilling jumbos. The main reason for employing mechanized drilling instead of a manual one depends on the speed, though in some degree it implies an increase of overbreak risk, accompanied by a reduction of precision at the moment of obtaining an expected contour after blasting (Brånnfors 2002).

Following the blasting process starts the ignition of the explosives, and the rock breaking. All these process are performed with a highly degree of accuracy in order to prevent possible detrimental effects on the standability of the walls and roofs of tunnels and chambers. After the blasting round, which removes a determined

---

[16] *V-Cut or 'fan' cut, this is the most efficient excavation using DB method; this is obtained when the fume pushes the rock against a free surface. The blast holes in the central part are arrange conically and ignite first, then the surrounding blast holes are ignited consecutively with a delay of milliseconds. In this way progressively the rock is pared, from the cut to the contour (Johansen 2000)*

amount of rock, the ventilation takes place, to extract the fumes produced ($CO_{2,}, CO, NO_x$) and then the muck removal starts- The removal process consists in

loading up the muck, transporting it (haulage), and unloading it at the spoil tip. For the removal from the tunnel, and further transportation to the spoil tip are employed usually skid steers (wheeled loaders), trackless transport as trucks (rail). Another option is the use of a crusher, conveyor belt and mucking trains, the best method for haulage, addressed as a “high performance drill and blast excavation concept” (Zare 2007).

In Norwegian tunneling, the tunnel is normally excavated for 5 days per week, two shifts per day and 10 hours per shift. This results in an average of 101 working hours per week during a year (Zare 2007)

Figure 10 General information of the tunneling process and sources; Assumption considered at the inventory construction

Underground Construction Information	***info***	***source***
Shift/day	2	*(Zare,2007)*
Cycles/shift	3	*(Panthi,2011)*
Distance excavated/week	75	*(Zare,2007)*
Years of work	*3*	*(Sira-Kvina, 2007)*
Cross section (m2)	120	*(Sira-Kvina, 2007)*
Total Muck remove (tones)	1,50E+06	*(Sira-Kvina, 2007)*

Most of the hydropower tunnels built in Norway have only 2-4% concrete or shotcrete lining, thanks to favorable tunneling conditions, as well as to the “support philosophy, which accepts some falling rocks during the operation period of the water tunnel” (Broch 2010).

It is considered as part of the operation taking place at the DB the transportation of the workers per shift at the tunneling process.

Other equipment and activities related to the DB operations are not being considered due to lack of information and sources. Among These are transportation of water by pumps, ventilation via blowing air considering amount of air required for the proper functioning (combustion) of the diesel driven muck equipment (Appendix C), and last the energy supply to electric equipment utilized inside the tunnel as a compressor for air supply and water.

4.2.4.1.2. Underground process inventory (tunneling)

In the tunneling process includes excavation, mucking, support work and lining work. Regarding the excavation in the inventory is considered the diesel burned by the Jumbo drill and the Jumbo drill rods consumed; calculated respectively as the total amount of steel per drill rod times and the total amount of drill rods consumed during the whole construction (Appendix D). It is also considered the transportation from the manufacturer place (drill rods) until Tonstad.

The blasting process of the muck, the rock crushing before the process of mucking, and the transportations of the workers in a small bus during each cycle is part of the inventory (Appendix C).

Table 10 Main activities taking place during the construction of the Underground facilities (D&B)

Table: Underground Construction
Excavation
Lining (concrete)
Muck Removal
Lining (steel) Pressure Shaft
Support Work Tunnel
Support Work Chamber

[17]The main estimation regarding this sub-part of the inventory includes:

- Durability of cycles of each drill rod, therefore the total amount of steel consumed during the construction of the underground facilities *(useful life 200 shifts per unit).*
- Total consumption of diesel by the Jumbo drill machine.
- No differentiation between the constructions of the operational chamber, the tunnel of access, pressure shaft and the headrace/ tailrace. It is assumed that

[17] *Professor Krishna Panthi, gently provided most of the information and assumption that have been used as base for the completing it the inventory (Panthi 2011).*

the whole tunnel extension is built considering the available data of the cross section of the headrace/ tailrace, and pressure shaft.

- Transportation distance of the drill rods from the manufacturing place (ground transport & sea transport).
- Transportation of the crew during each shift at the DB process.

In the case of Tonstad has been assumed that the mucking process is done using trucks Ideally, dumpers should perform this process, but there is no available inventory data at the Ecoinvent v. 2.2 (2008) data set[18]..Because of this it has been assumed the utilization of lorries of 28 tones instead of dumpers, but since dumpers usually have a capacity of 35 tones, substituting them with the lorries. Implying an over utilization of resources and increase of trips for transporting the muck outside the tunnel (six more trips per shift).To obviate this problem is assumed the use a lorry with 28 tons of capacity but the total amount of trips, necessary for the haulage of the 1.5E+06 tons of muck excavated, is calculated considering dumpers with capacity of 35 tones.

In the case of Tonstad has been assumed that trucks do the mucking process. Ideally, dumpers should perform this process, but there is no available inventory data at the Ecoinvent v. 2.2 (2008) data set. Because of this has been assumed the employment of lorries of 28 tones as dumpers. This assumption implies an over requirement of resources and increase of trips for transporting the muck outside the tunnel. Usually the dumpers have a capacity of 35 tones, implying an increase on six trips per shift. As an assumption has been employed the lorry with 28 tons of capacity but assuming the total amount of trips if dumpers with capacity of 35 tones were employed for the haulage of the 1,5E+06 tons of muck excavated.

[19] A considerable portion of the tunneling process consists of supporting activities, realized by employing structural steel, while in case of hydropower tunnels the use

---

[18] *Actually for tunnel with the specification of Tonstad the type of haulage employed is tackles, due to the costa and the speed of the process that can be achieved (Zare 2007)*

[19] *Typical Rockbolt (Portland Bolt & Manufacturing, Inc., 2011.)*

of tubular rock bolts is widely used, usually with expansion anchors that are grouted or shotcrete[20]. The rock bolts varies in size depending on whether it's used for supporting the walls at tunnel or at chambers.

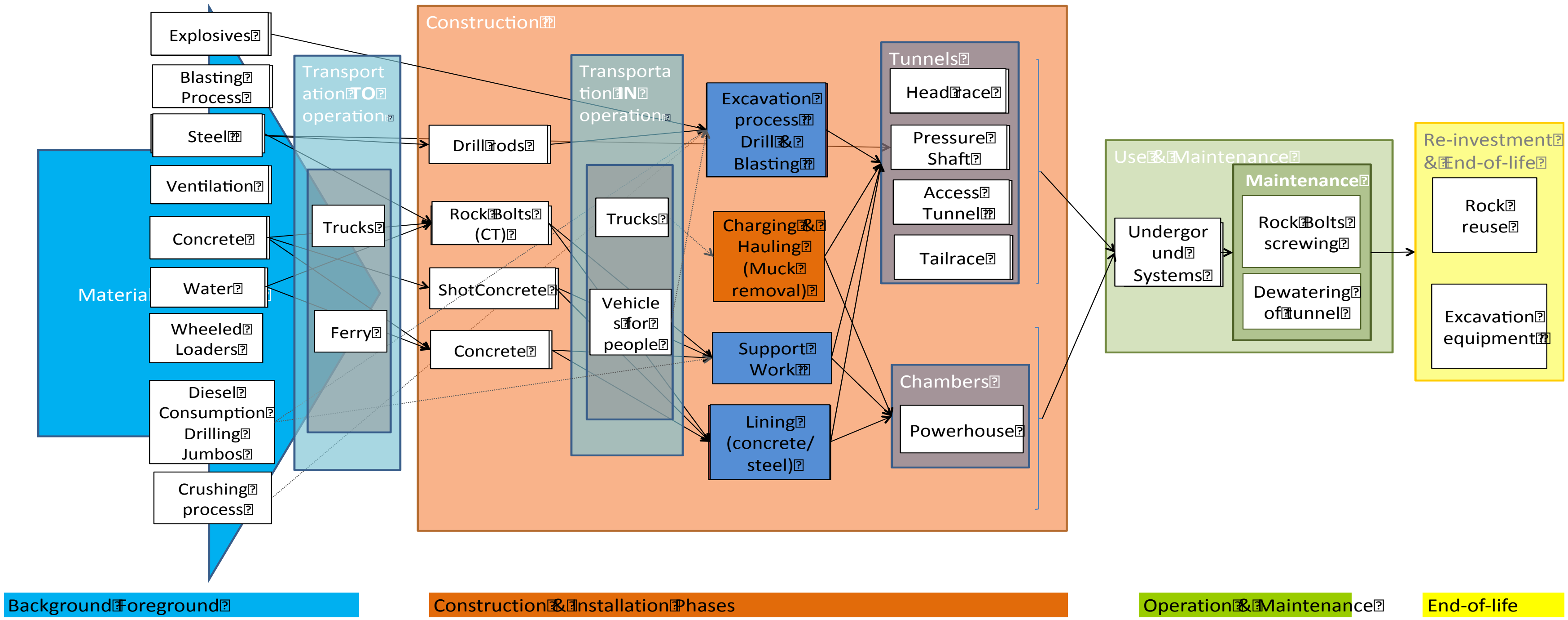
Table 11 Information utilized for the creation of the inventory for the rock bolts employed at the lining process, rock bolt figure in the upper left side

Support Work CT-Bolts	*radious (m)*	*Lenght (m)*	*Source*
Tunnels	*0,0255*	*2,1*	*(PortlandBolt Inc. , 20110)*
Chamber	*0,0255*	*3*	*(Panthi,2011)*

The ventilation process, which is energy intensive, was not consider due to lack of information available for compiling an inventory (refer to Appendix C). Rønn, (1998) argues that the ventilation process cost 30% on average of the total budget form excavating and underground tunnel with the DB method; this is a hint of the importance for future studies to take the ventilation process into account.
In relation to the lining process, as noted before between 2 and 4 % of the water tunnels in Norway are lined with concrete. Regarding the pressure shaft this is lined in steel (Sira-Kvina 2007) Maintenance along the use phase that is of 100 years, are considered to take place every ten years, where rock bolts are re screw and shotcrete is be applied. Below is presented a flow chart of the life cycle inventory of the underground facilities.

[20] *For practical reasons it has been assumed during the LCI that concrete is used for grouting instead of shotcrete*

Figure 11 Flowchart of the Inventory compiled for the life cycle of the Underground facilities



<u>Flow Chart Description:</u>

Construction & installation phase: Fuel consumption during construction, transportation, equipment & machinery (energy intensive process). Main materials employed during construction phase.

Operation & Maintenance: Replacement of some units from the reversible turbine, Lubricant and other maintenance procedures. Tunnel Dewatering Frequency 10 years

End-of-Life: Assuming that equipment in yellow that is mainly from metals can/should be recycle after it's dismantling.

4.2.4.2.Reversible Francis Turbine unit

The turbines, developed during the 18-century as a response to the requirement for more energy, are an evolution of the water wheels that couldn't satisfy the energy demand anymore. In 1975 Professor Segner invented a reaction runner, activated by the water jet that was the forerunner of the turbines. The engineer Burdin introduced the designation of turbine during the early 19-century; at that time the turbines had the capacity of producing between 20 and 30 kW (Kjølle 2001). Since then there has been an introduction of several varieties of turbines employed according to the head and the water discharged. At the present time the dominant turbines are Pelton, Francis and Kaplan and they supplement each other in an excellent way. Pelton turbines are used for relative high heads and small water discharge, Kaplan's for the lowest heads and largest discharges and Francis for regions located between the other two types.

The turbine that would be used at Tonstad III is a Francis turbine with the additional function of being reversible. The main parts of this type of turbine are presented below (Kjølle 2001).

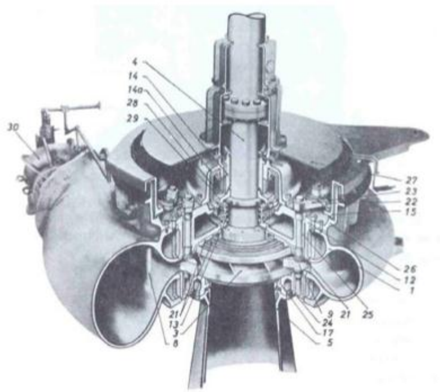


Figure 12 Picture of a Francis Turbine, components considered at the inventory are enumerated and described below (Kjølle 2001).

- -the *guide vane (9) cascade*, usually adjustable, gives the water flow the velocity and the direction required for the inlet to
- the *runner (3)* transfers the hydraulic power is to mechanical power on
- the *turbine shaft (4)* to which the runner is fixed. The turbine shaft is guided in a
  - - radial bearing and an
  - - axial bearing that is loaded with the axial force from the runner, caused by the water. Pressure and impulses from the flow, and the weight of the rotating parts.
- The *scroll case (1)* (casing) conducts the water flow to the guide vane cascade.
- The *draft tube (5)* conducts the water flow from the turbine outlet into the tale race canal.

The Power station would have an extra capacity of two units of reversible turbines with a total capacity of 980 MW. A unit consists of reversible Francis turbine of 560 MW, with a generator capacity of 125$^{m^3}/_{s}$, and a pump capacity of 100 $^{m^3}/_{s}$ (Sira-Kvina 2007). The reversible turbine is the same as the Francis turbine but with a bigger runner and a pump integrated. The runner is bigger than the standard Francis turbine because its design prioritizes the turbine mode in relation to the high head of the plant where it will be functioning. The high head at Tonstad is of 480 m.

4.2.4.2.1. Reversible Francis Turbine Inventory process

The inventory developed only takes into consideration the materials used for manufacturing the main parts of the turbine and the transportation from the manufacture site until the plant. A set of interviews with specialist was held In order to obtain the main information related to the turbine components and amounts of materials per component (Dahlhaug 2011; Walseth 2011).

Table 12 Reversible Francis turbine components considered at the inventory compiled

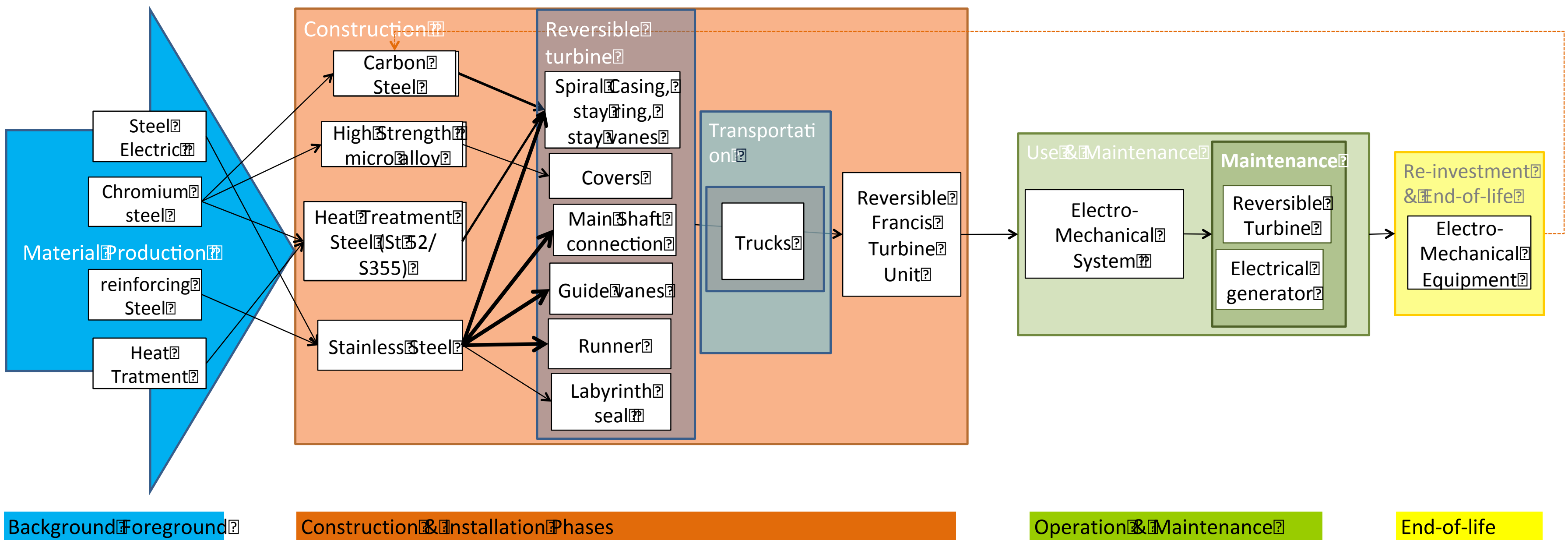
Table : Construction Reversible Francis Turbine		
Spiral Casing	Unit	1
Covers	Unit	1
Guide Vanes	Unit	1
Runner	Unit	1
Labyrinth Seal	Unit	1
Main Shaft (connected to pressure shaft)	Unit	1

The main information gathered from the interviews was related to the principal components, its composition (for type of material and amount of materials per component refer to Appendix E and the turbine lifetime.

The lifetime varies according to the parts and their exposure to water, on average the whole unit has a life time of 30 years, with the exception of the Labyrinth Seal which can last for over 80 years, and the runner and the guide vanes have to be replaced after 15 years, while the spiral casing every 30 years (O. G. Dahlhaug 2011). Concerning the specific materials employed for the construction of the different parts of the Turbine these were not available at Ecoinvent v. 2.2 (2008), that is why similar materials available were chosen .Following is presented the flowchart of the inventory compiled for the reversible Francis turbine.

The main shaft is the connection with water tunnel more exactly with the pressure shaft excavated at the underground tunnel (Sira-Kvina 2007; Toshiba Co. 1985) It is constructed base on metal, in the inventory is considered as part of the labyrenth seal.

Figure 13 Flowchart of the Inventory compiled for the life cycle of the reversible Francis turbine



<u>Flow Chart Description:</u>

At the construction & installation phase of the Reversible turbine are only taken in into account d the main materials and transportation from the manufacturing place until Tonstad III

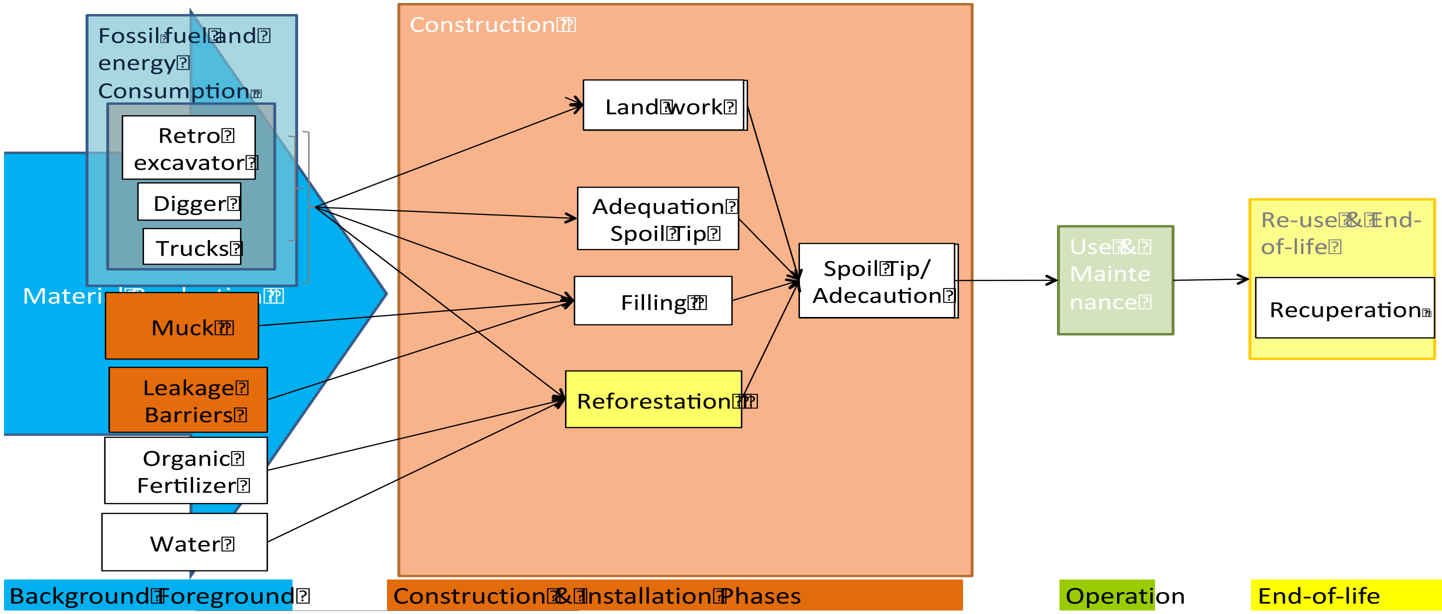
At the operation & maintenance phase some of the main components from the reversible turbine are replaced according to their life time

At the end-of-Life, units from reversible turbine are being dismantle are the metal components recycled.

4.2.4.3.Spoil Tip

The description provided by Sira-Kvina (2007) regarding the specification of the work and processes to be develop at the construction and further management of the inert material extracted is limited. It established that the site would be located on proximity of the outlets of the tunnel. A reforestation process would take place after the mucking is over. The total extension of the Spoil tip is of 96 acres.

Figure 14 Flowchart of the Inventory compiled for the life cycle of the Spoil Tip



Flow Chart Description:

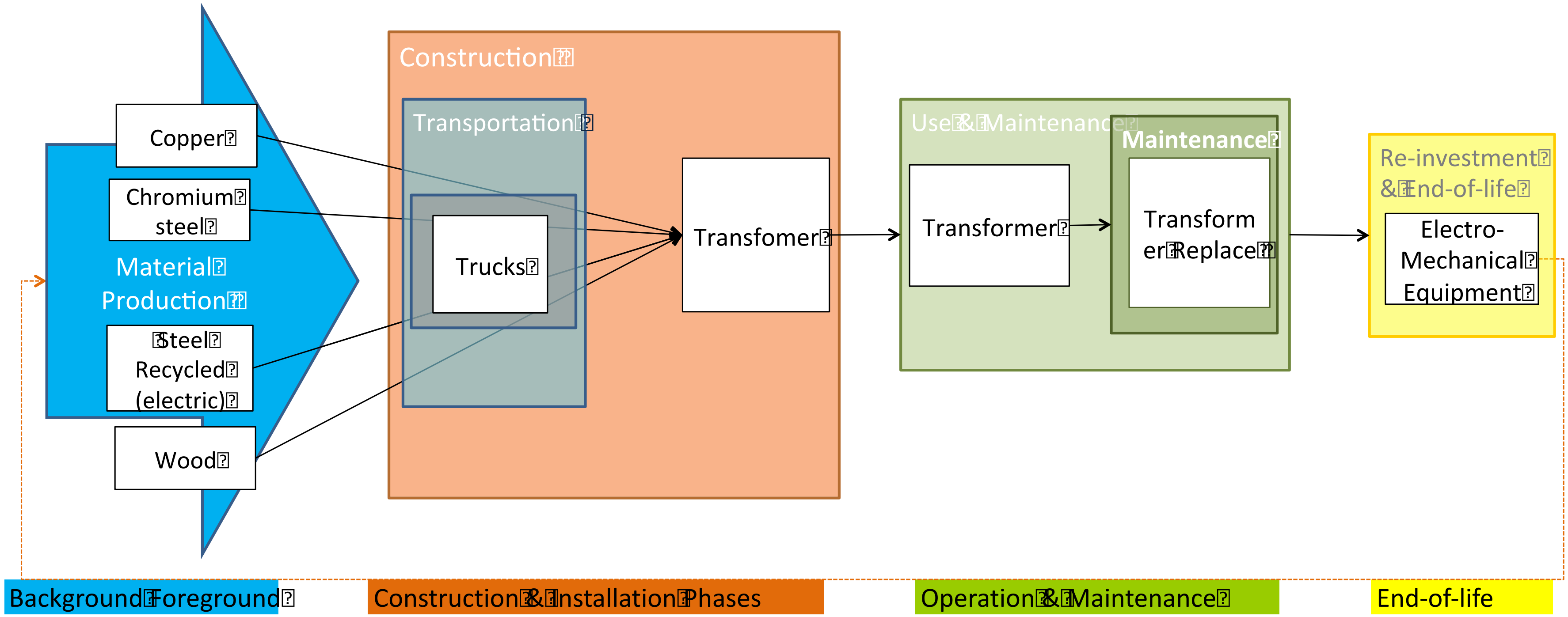
Construction & installation phase: Main materials and transportation and machinery requirements are take-in into account

No operation and maintenance process are considered during the end-of-Life:

4.2.4.3.1. Transformer

Tonstad II development would require an installation of the step up transformer per reversible turbine with a configuration of 560MVA. The transformer has a lifetime of 50 years per unit. The inventory employed has been compiled by (Jorge 2011)

Figure 15 Flowchart of the Inventory compiled for the life cycle of the transformer



4.2.5. Life cycle Inventory proposed

The next table presents the life cycle inventory compiled for this study. On the Appendix E is presented an inventory with more detail

Table 13 Life cycle inventory compiled for the Pumped Storage Hydro Plant at Tonstad III

Life Cycle Inventory Table

	Process at Background Foreground	Per Pumped Sto	Unit
Underground	Blasting	1,13E+06	m3
	Drill rods steel	5,56E+05	m3
	Shotcrete Concrete	7,40E+05	m3
	Crushing roch at Mucking	1,13E+09	kg
	Equipment Energy consumption	2,80E+06	MJ
	Hydraulic Digger at excavetion	9,74E+05	kg
	Wheel loader at Excavation	3,92E+05	m3
	Rock bolts steel	1,61E+08	kg
	Shotcrete water	1,36E+05	tkm
	Transport by sea of equipment	1,27E+08	tkm
	Dumpers & Transportation of materials	5,56E+08	tkm
	Transport of personal	1,03E+04	units
Reversible Francis Turbine	Laberynth Seal	1,31E+04	kg
	Spiral Casing	6,52E+08	kg
	Laberynth Seal	8,51E+04	kg
	Laberynth Seal	1,31E+04	kg
	Transportation equipment	5,32E+08	tkm
Spoil Tip	Muck	5,25E+06	kg
	Muck Transport	1,10E+06	tkm
	Filling	1,50E+06	m3
	Reforestation	9,60E+02	kg
Transformer	Transformer	5,36E+04	kg
	Transformer	4,00E+04	kg
	Transformer	9,96E+04	kg
	Transformer	1,50E+04	kg
	Transformer	8,73E+04	tkm
Maintenance	Maintenance of Tunneñ	1,95E+05	m3
	Replecement of Metal equipment	2,01E+05	kg
	Replecement of Metal equipment	1,99E+05	kg
	Replecement of Metal equipment	7,99E+04	kg
	Replecement of Metal equipment	2,24E+05	tkm
	Maintenance of Tunneñ	2,46E+04	kg
	Replecement of Metal equipment	3,00E+04	kg
	End-of-Life	6,54E+08	kg

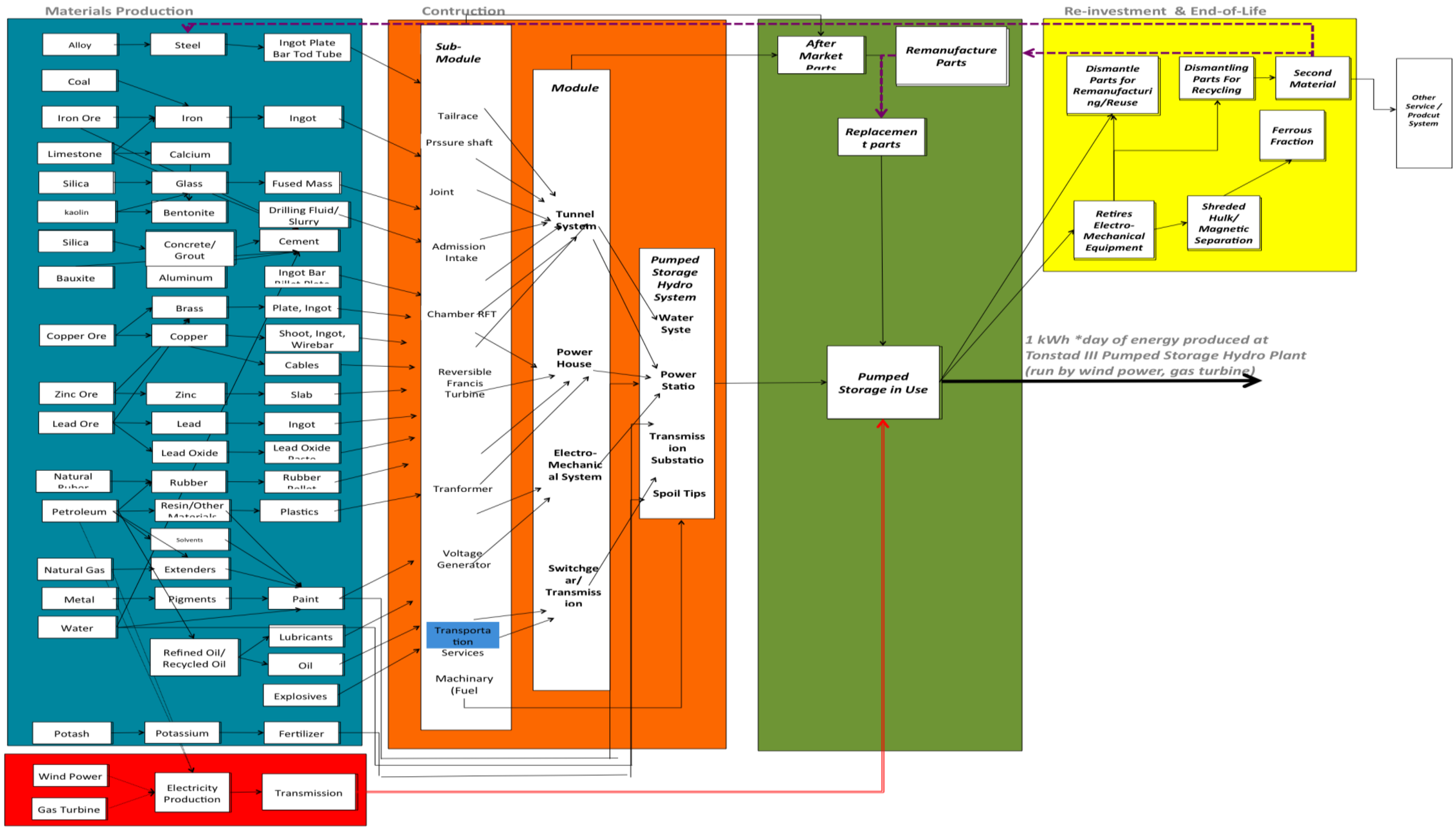


Figure 16 General Flow Chart of the life cycles Inventory performed to the Pumped Storage Hydro Plant

5. Results

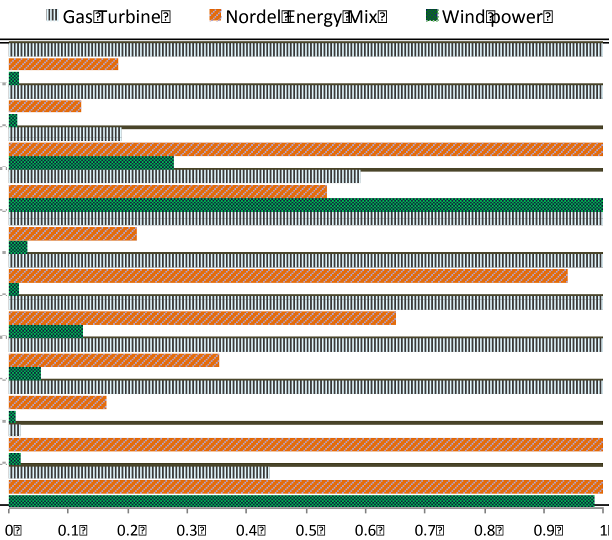
The environmental impact assessment was performed using the LCA_gui v13.2software, and the organization of the results using Excel. In this chapter are presented the overall environmental impacts and then the overall results for three specific scenarios. Among them two make reference to the load electricity services during peak hours of demand, these are gas turbine and wind power. The third option, characterized by the Nordel mix, provides the possibility of feeding the c-d cycle not only with generation technologies employed for the peaking components, but also with a mix of generation technologies used for base, middle and peak component. This option results particularly appropriate when the operation of the pumped storage plant is oriented towards generating the highest economic profit, by buying cheap electricity during low demand hours of the day and selling it during peak hours. The electricity bought can be from any source *(and not necessary from generating technologies employed to provide electricity during the hours)* as gas turbine and wind power

5.1. Overall impact of pumped storage hydro plant

The results of the environmental appraisal performed in relation to the pumped storage hydro power plant along the life cycle are reported on table. The impact categories evaluated, introduced at table, were selected according to their relevance with the system assessed. The operation phase presents the worst environmental performance, followed by the construction process. During operational phase, the plant is subjected to significant losses depending on its operational efficiency along its functional life *(that in this study has been assumed to be of 100 years)*. The environmental performance at the operational phase is highly dependent on the pumping mode, shaped by the electricity source. This implies a variation of the total emissions according to the emissions of the source. The values are presented in the graph of the table 14, the emissions have been normalized against the highest emission record at each impact category. The electricity produced by gas turbine plant is by far the worst one, having the highest score in seven of the eleven impact categories evaluated.

Table 14 Overall environmental benchmark of the life cycle of running a c-d cycle by each of the generation technologies under assessment, scores have been normalized against the highest environmental contribution

Pumped Storage FU: 1MJ*day		***Gas***	***Nordel***	***Wind***
CC	*g CO2-Eq*	3.24E+02	5.94E+01	5.43E+00
FD	*g oil-Eq*	1.29E+02	1.56E+01	1.64E+00
HT	*g 1,4-DCB-Eq*	3.34E+00	1.76E+01	4.86E+00
MD	*g Fe-Eq*	3.31E+00	3.00E+00	5.60E+00
POF	*g NMVOC*	5.94E-01	1.27E-01	1.82E-02
WD	*m3*	8.89E-04	8.34E-04	1.58E-05
PMF	*g PM10-Eq*	1.42E-01	9.26E-02	1.77E-02
TA	*g SO2-Eq*	4.36E-01	1.53E-01	2.33E-02
NLT	*m2*	5.55E-05	9.13E-06	5.92E-07
ALT	*m2a*	1.18E-04	5.96E-03	1.13E-04
ULT	*m2a*	1.46E-04	3.34E-04	3.29E-04

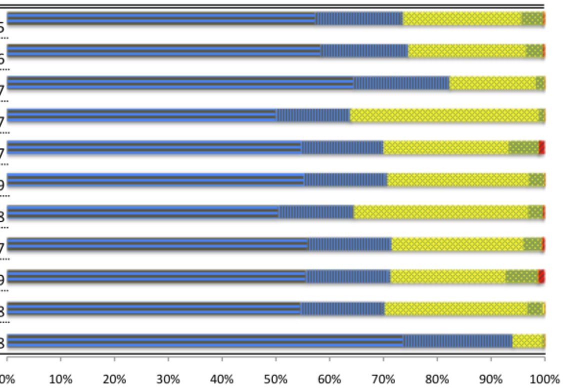


The electricity input from the wind turbine to run the pumping mode of the plant and afterwards to produce $1MJ * Day$ indicates a total climate change impact of

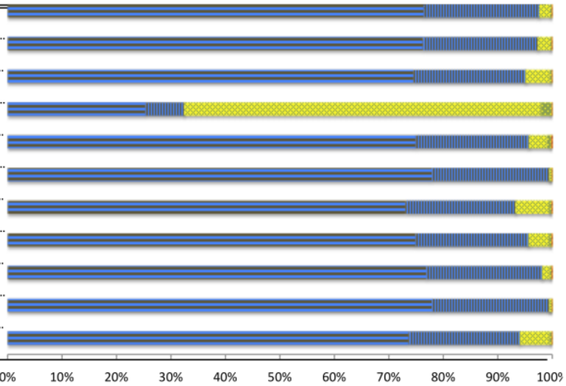
5.45g CO2-Eq, while in the case of the Nordel mix is 59,4 g CO2-eq and of Gas electricity is 324 g CO2-Eq. The Climate Change impact produced by the plant when is storing electricity produced from running a gas turbine is almost 60 times bigger in terms of emissions than when the electricity is produced by wind turbines.

The distribution of environmental impacts along the different phases of the plant life cycle can varies significantly depending on the electricity that is feeding the system. For example in the case of wind power the operational phase counts for 73.6% of the climate change emissions totally emitted, while when it comes to gas turbine electricity the operational phase contributes with 99,6% of the total climate change emissions, Nordel mix is has a similar share too. The following set of figures presents the total impact for each of the electricity input options.

Electricity input from Wind power plant FU: 1MJ*day		*Opetarion*	*Construction*	*End-of-Life*
CC	*g CO2-Eq*	4.00E-03	1.42E-03	1.49E-05
FD	*g oil-Eq*	1.23E-03	4.13E-04	5.21E-06
HT	*g 1,4-DCB-Eq*	4.00E-03	8.62E-04	7.58E-07
MD	*g Fe-Eq*	3.57E-03	2.03E-03	3.63E-07
POF	*g NMVOC*	1.27E-05	5.25E-06	2.05E-07
WD	*m3*	1.11E-05	4.61E-06	8.37E-09
PMF	*g PM10-Eq*	1.14E-05	6.21E-06	6.07E-08
TA	*g SO2-Eq*	1.67E-05	6.53E-06	1.20E-07
NLT	*m2*	4.22E-07	1.62E-07	7.33E-09
ALT	*m2a*	7.94E-05	3.37E-05	1.94E-08
ULT	*m2a*	3.09E-04	1.98E-05	2.82E-08



Electricity input from Nordel mix plant FU: 1MJ*day		*Opetarion*	*Construction*	*End-of-Life*
CC	*g CO2-Eq*	5.80E-02	1.42E-03	1.49E-05
FD	*g oil-Eq*	1.52E-02	4.13E-04	5.21E-06
HT	*g 1,4-DCB-Eq*	1.67E-02	8.62E-04	7.58E-07
MD	*g Fe-Eq*	9.72E-04	2.03E-03	3.63E-07
POF	*g NMVOC*	1.22E-04	5.25E-06	2.05E-07
WD	*m3*	8.29E-04	4.61E-06	8.37E-09
PMF	*g PM10-Eq*	8.64E-05	6.21E-06	6.07E-08
TA	*g SO2-Eq*	1.47E-04	6.53E-06	1.20E-07
NLT	*m2*	8.96E-06	1.62E-07	7.33E-09
ALT	*m2a*	5.93E-03	3.37E-05	1.94E-08
ULT	*m2a*	3.14E-04	1.98E-05	2.82E-08



Electricity input from Gas turbine plant FU: 1MJ*day		*Opetarion*	*Construction*	*End-of-Life*
CC	*g CO2-Eq*	3.23E-01	1.42E-03	1.49E-05
FD	*g oil-Eq*	1.29E-01	4.13E-04	5.21E-06
HT	*g 1,4-DCB-Eq*	2.48E-03	8.62E-04	7.58E-07
MD	*g Fe-Eq*	1.28E-03	2.03E-03	3.63E-07
POF	*g NMVOC*	5.88E-04	5.25E-06	2.05E-07
WD	*m3*	8.84E-04	4.61E-06	8.37E-09
PMF	*g PM10-Eq*	1.36E-04	6.21E-06	6.07E-08
TA	*g SO2-Eq*	4.29E-04	6.53E-06	1.20E-07
NLT	*m2*	5.53E-05	1.62E-07	7.33E-09
ALT	*m2a*	8.45E-05	3.37E-05	1.94E-08
ULT	*m2a*	1.27E-04	1.98E-05	2.82E-08

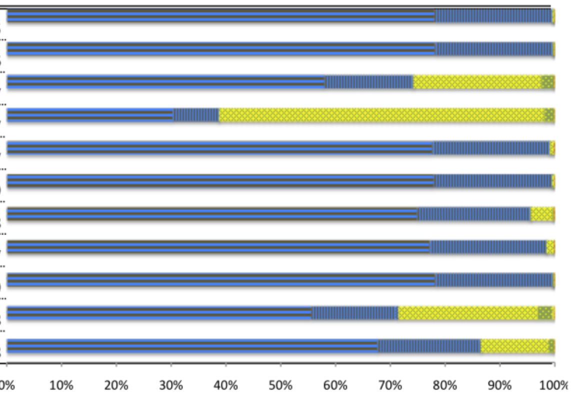


Table 15 Life cycle impact of a pumped storage hydro, for different electricity sources, and breakdown among relevant process.

6. Analysis

The overall results of the life cycle of the pumped storage hydro plant have shown that at least 70 % of the total environmental impact evaluated occurs during the operational phase, in accordance to the last observation that the emissions are highly dependent on the type of electricity stored by the plant.

6.1. What information do the existing literature and case studies provide of the environmental impacts and benefits of pump-storage hydropower? What are the Strengths and weaknesses?

Along the literature review presented at chapter 2has been possible to disclosure several facts and aspects of the overall environmental performance of hydropower plant, but regarding pumped storage hydro plants there are not so many studies available. The existing environmental studies have been performed using different approaches and evaluating specific impacts happening as a consequence of the plant operation. Life cycle assessment sets of studies are the only ones that assess other phases besides the operation, as the construction and dismantling and in most of the cases have been employed to assess hydropower plants.

Most of the traditional studies had researched upon the environmental impacts of hydropower production on “long term impacts of river and lake regulation in general bypass sections migration barriers and minimum flow of water needed to secure no modification on conditions for the biota”(Cedren & Sintef 2008). According to these studies along the year and depending the seasons there are specific alterations on the natural environment in relation to hydraulic conditions. In the the case of Norway,the alterations can be drastic due to the geographical location, because of ice formation, temperature changes, substrates alteration and erosion. In addition the possibility of abrupt changes on the downstream flow due to operational reasons, can strongly affects the oragnisms because of alterations in their habitat. Factors as ramping rates, cover, substartes, season and light comditions can affect fish behaviour.

At the present time even though knwoledge of hydropeaking impact on the biota is available, there are still major gaps, that's why CEDREN (Cedren & Sintef 2008) is developing a research aimed to provide a better understanding of the impacts that the operational phase of a hydropower plant has upon the aquatic biota and other organism like mamals and birds, in terms of modification of the levels of substrate composition, creation of erosion, silation procress, changes of the water temperature

The LCA studies performed to hydropower plants have been applied to plants with different settings. Most of these studies highlight the environmental implication of the construction of the dams, (Farre 2007; Friedrick & Marheineke 1994; Gagnon & Vate 1997; Statkraft & Ostfold 2006). Land transformation is a recurrent impact due to the large amount of land required for the construction of the dams; another aspect occurring during the operation phases is the potential production of biomass depending on the specific climatic conditions where the plant is located. This last issue is not relevant in the case of Norway because of the low temperatures during the year (Gagnon et al. 2002; Schuller & Albrecht 2008). Whilst GHG is always reported to be the main anthropogenic set of emission that this type of plant incurs on.

An LCA has been performed evaluating different electric generation options. According to the results run of river and reservoir hydropower plants were assessed to have the best environmental performance regarding GHG emission, nuclear power was also showing a good performance, but without considering the disposal phase. Two additional performance categories were evaluated: 1) direct land requirement ($^{km}/_{TWh}$) that evaluates the energy requirement in order to produce a TWh of electricity and 2) energy payback ratio

($^{energy\ output}/_{energy\ input}$) that assesses the total amount of energy produced compared to the energy required for constructing and operating the generation facility.

Even if hydropower with reservoir scored worse compared to other renewable energy options as wind and solar regarding the direct land requirements, at the same time it should be considered that the other two generation options are intermittent sources of electricity due to their dependency upon external factors, with all the disadvantages that this implies. Concerning the energy payback ratio (introduce at chapter 2) the hydropower with reservoir boosts one of the highest performances and the best solution, after the one that is provided by hydro run of river. These results are presented at table 6.

The major strength of the pumped storage system relies on the possibility of assuring a continuous inflow of electricity during a longer period of time through the provision of ancillary services to renewable intermittent sources, while dismantling existing electricity generation option with higher anthropogenic emissions.

A weakness of this type of plant and of hydroplant is the high dependency of the environmental performance on the location where the plant is constructed. The environmental impact can vary dramatically as a consequence of the stratification of the water in the presences of warm air conditions boosting the decomposition of organic matter and the release of methane (Farre 2007; Gagnon & Vate 1997)

Another factor of environmental impact that can be considered as a weakness of the system it's the usually remote location requiring transmission lines and substation to transport the electricity generated from and to the pumped storage plant, increasing the demand for equipment and operations (this has been excluded from the system under study).

There is still lack of knowledge regarding how the HydroPeaking, implying an intensive operation regime of the pumped storage plant, would affect the aquatic biota (Cedren & Sintef 2008).
A more robust benchmark between electricity storage options shall be conducted in the future, few LCA studies have been found allowing benchmarking them. Hydropower and pumped storage facilities are highly site-specific making it impossible to predefine a general performance, especially in the case of multipurpose plants like an irrigation plant.
For this assessment has been define a whole life of 100 years for the plant, but in reality once a tunnel of these characteristics has been built this type of plant is likely to continue working after that.

6.2. What is the process chain involved, including of the efficiency of the processes?

The pumped storage facility allows storing electricity during a period of time and this is realized through the construction of the plant, the operational phases and further deployment which undertakes the life cycle of the facility. During the operational phase in order to run a c-d cycle the following chain of process takes place: electricity is generated from a specific source, which is employed for running the pumping mode of the turbine that converts the electricity into potential energy stored at upper reservoir. After a defined period of time the water stored that has been pumped is released from the reservoir so that the potential energy is converted

The electricity employed by the plant can be produced by any type of generation technologies, while the operational regime can vary depending on the requirement of electricity. During this c-d process there is a loss of energy due to the existing efficiency when using the electricity to run the turbines and pump the water up to the reservoir, this loss of energy has been allocated in a dummy variable in order to account for the environmental burden associated (figure 7). The amount of energy that is lost in order to produce 1MJ*day, is of 0,257 MJ *day. The efficiency of the plant is assumed to be of 78 %.

The environmental impact generated by the pumped storage plant varies according to the electricity running the c-d cycle. The pumped storage hydro has been assessed utilizing three different types of electricity to run a cycle, and for all the three cases the environmental impact linked to the electricity loss is near to 20% of the total impacts in each of the eleven categories evaluated. For the gas turbine this loss is responsible of 18.9% of the emissions, while for the Nordel mix of 19.6 %, and for the wind power of 15.8% of the overall environmental impact (Appendix F).

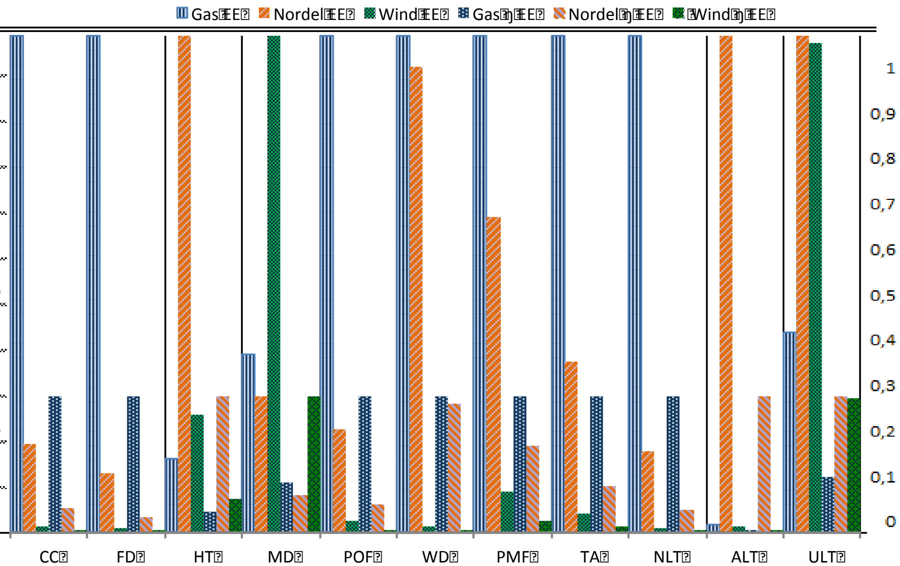
The electricity produced by the wind power to run the c-d cycle of the plant has the best environmental performance considering most of the categories, being metal depletion and urban land transformation the only two categories where it has a considerable higher impact than Gas turbine and Nordel Mix electricity. In the case of metal depletion the potential impact category is registered to be 2. 5 times higher than the one of gas turbine and almost the same compared to Nordel mix. Regarding urban land transformation the wind power electricity has a value 2.7 times bigger than gas turbine electricity, and 3.7 times bigger than Nordel Mix. These results are presented at table 16, the values in the graph have been normalized against the highest score for each of the impact categories. The environmental impacts derived from the electricity that cannot be stored because of its dissipation is higher than the direct environmental impacts of the electricity stored when the Nordel mix and wind turbine are employed at the c-d cycle. Regarding the climate change environmental impact attributable to the proportion of electricity dissipated, in the case of gas turbine is of 69,7 g CO_2-eq and of fossil depletion category is 12.5 g CO_2-eq. Regarding the direct impact attributable to the stored energy, when Nordel mix and wind turbine feeds the c-d cycle is of 45.1

g CO_2-eq , and 3.11 g CO_2-eq respectively. In the case of fossil fuel depletion it is of 19.1 g CO_2-eq and, 0.91 g CO_2-eq subsequently

.

Table 16 Environmental emissions along associated to the operational phase of the life cycle plant, comparison of the performance per type of electricity running the system. Differentiation of environmental impacts between energy store and losses (efficiency); values at graph have been normalized agaismt the highest contribution

Pumped Storage FU: 1MJ*day		*Gas EE*	*Nordel EE*	*Wind EE*	*Gas η EE*	*Nordel η EE*	*Wind η EE*
CC	*g CO2-Eq*	2.53E+02	4.55E+01	3.11E+00	6.97E+01	1.25E+01	8.58E-01
FD	*g oil-Eq*	1.01E+02	1.19E+01	9.60E-01	2.78E+01	3.28E+00	2.64E-01
HT	*g 1,4-DCB-Eq*	1.94E+00	1.31E+01	3.13E+00	5.34E-01	3.61E+00	8.63E-01
MD	*g Fe-Eq*	1.00E+00	7.61E-01	2.80E+00	2.77E-01	2.10E-01	7.71E-01
POF	*g NMVOC*	4.61E-01	9.55E-02	9.93E-03	1.27E-01	2.63E-02	2.74E-03
WD	*m3*	6.93E-04	6.50E-04	8.70E-06	1.91E-04	1.79E-04	2.40E-06
PMF	*g PM10-Eq*	1.07E-01	6.77E-02	8.91E-03	2.94E-02	1.86E-02	2.46E-03
TA	*g SO2-Eq*	3.36E-01	1.15E-01	1.30E-02	9.26E-02	3.17E-02	3.59E-03
NLT	*m2*	4.33E-05	7.02E-06	3.29E-07	1.19E-05	1.93E-06	9.06E-08
ALT	*m2a*	6.57E-05	4.65E-03	6.17E-05	1.81E-05	1.28E-03	1.70E-05
ULT	*m2a*	9.91E-05	2.46E-04	2.42E-04	2.73E-05	6.77E-05	6.67E-05



6.3. What are the important energy inputs and material requirements along the process chain?

Throughout the environmental breakdown of the pumped storage plant while the construction and dismantling phases present the same environmental consequences in the three cases evaluated, this is not the case of the operational phase which presents robust differences.

The environmental impacts generated when running a c-d cycle with a specific electricity input are mostly a consequence of the inherent emissions of the electricity generating technology and partly of the losses at the pumped storage operation. When the plant runs using wind power electricity the whole system has a significantly less environmental intensive performance at all the categories, than when it runs using any of the other two options (gas turbine and Nordel mix). When wind power electricity is employed, it contributes in the best case for at least 64% of the total emissions occurring (table 17). For the other two options this value is on average 90% for most of the impact categories considered. The next table provides more detailed information about this last point throughout all the phases of the plant life cycle. The only category of environmental impact that is bigger when employing wind power is that of metal depletion: 5,6gFe-eq, almost doubling the gas turbine 3,31gFe-eq contribution and 3gFr-eq for Nordel mix.

Table 17 Comparison of environmental contribution along the life cycle phases for each electricity supply option.

	*Gas Turbine at Pumped Storage FU 1JMJ *Day LC-Phases*			*Nordel at Pumped Storage FU 1JMJ *Day LC-Phases*			*Wind Power at Pumped Storage FU 1JMJ *Day LC-Phases*		
	Operation	*Construction*	*End-of-Life*	*Operation*	*Construction*	*End-of-Life*	*Operation*	*Construction*	*End-of-Life*
CC	99.56%	0.44%	0.00%	97.59%	2.38%	0.02%	73.65%	26.08%	0.27%
FD	99.68%	0.32%	0.00%	97.32%	2.64%	0.03%	74.60%	25.09%	0.32%
HT	74.17%	25.81%	0.02%	95.10%	4.90%	0.00%	82.26%	17.73%	0.02%
MD	38.74%	61.25%	0.01%	32.40%	67.58%	0.01%	63.77%	36.22%	0.01%
POF	99.08%	0.88%	0.03%	95.72%	4.12%	0.16%	70.00%	28.87%	1.13%
WD	99.48%	0.52%	0.00%	99.45%	0.55%	0.00%	70.70%	29.24%	0.05%
PMF	95.59%	4.37%	0.04%	93.23%	6.71%	0.07%	64.48%	35.17%	0.34%
TA	98.47%	1.50%	0.03%	95.66%	4.26%	0.08%	71.49%	28.00%	0.52%
NLT	99.69%	0.29%	0.01%	98.14%	1.78%	0.08%	71.34%	27.42%	1.24%
ALT	71.48%	28.51%	0.02%	99.43%	0.57%	0.00%	70.20%	29.78%	0.02%
ULT	86.47%	13.51%	0.02%	94.06%	5.93%	0.01%	93.98%	6.01%	0.01%

The Structural path analysis (SPA) for climate change impact category, performed for the plant when run by wind power and gas turbine, reveals the distribution of the impacts throughout the operational phases. In the case of the gas turbine 75 % of the climate change impact category is related to the burning of natural gas at the power plant Considering the wind power a similar trend is revealed, with this impact category (climate change) depending mostly on the materials used for the construction of the wind farm. The same tendency appears along the several path analysis (SPA) evaluated for the other impact categories (Appendix H)

The environmental contribution of the construction and the dismantling phases of the plant are presented at figure 17. The construction phases have been breakdown in several subcategories: activities, underground facilities, reversible Francis turbine, transformer, and spoil tip. At the same time each of these sub categories has been divided into the main activities that take place during the construction process. The same has been done for the maintenance operations, while regarding the end of life stage is only presented the dismantling of the metal component of the pumped storage plant. The detailed inventory is presented at the Appendix E. The activities that contribute the most to the several impact categories evaluated are: support work, main pressure shaft, excavation, and lining process. The main materials required during the Support work are: steel for the rock bolts employed and concrete that is applied as shotcrete on the walls of the tunnels. Stainless steel and chromium steel are necessary for the main shaft, which is employed for connecting the water inlet of the turbine with the pressure shaft at the water tunnel. The excavation process involves a blasting process and requires energy for running the jumbo drill and steel for the drill rods employed by the jumbo drill. These can be observed at the SPA performed to the system.

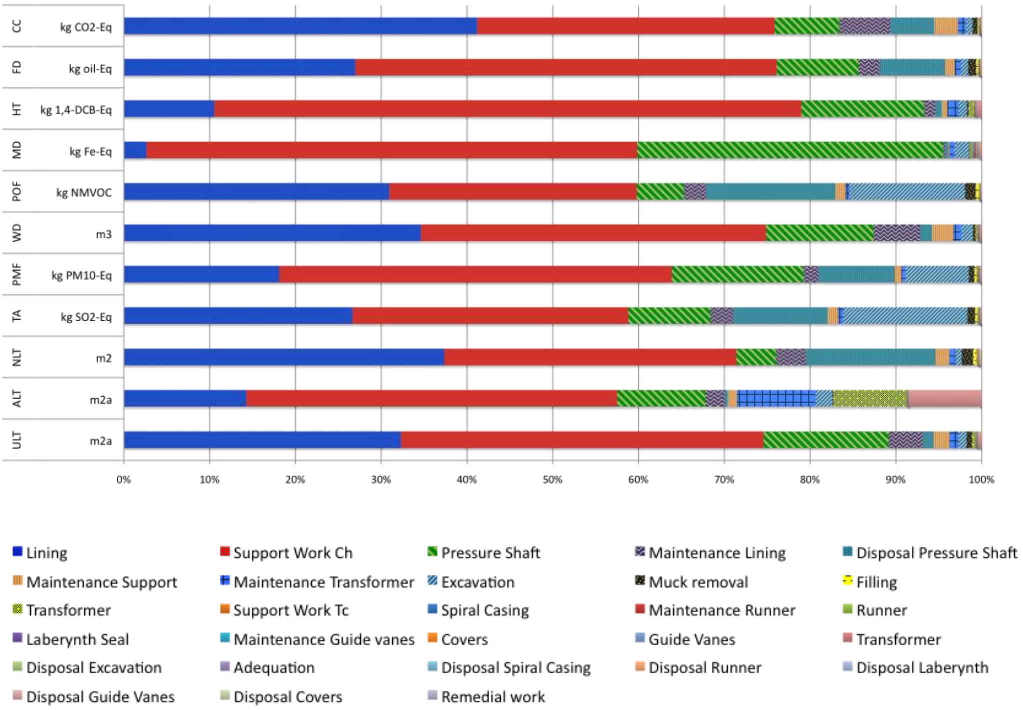


Figure 17 Environmental contributions from the construction, maintenance and dismantling phases along the life cycle of the pumped storage plant.

At Appendix I is provided a detailed breakdown of the contribution to the impact categories evaluated per main material and/or process (excluding the operational phases). When this information is used jointly with the results of the SPA it allows tracing down which are the main components along the life cycle of the pumped storage that are contributing to a specific impact category, because of the demand of a specific resource and process.

A 37% of the climate change impact is associated to the use of clinker, which is employed for the manufacturing of concrete that used as shotcrete for the lining at the underground facility. While a 7 %t is due to the transportation operations taking place.

The blasting process that is a main activity in the construction of the underground facilities contributes for a 17 % of the total terrestrial acidification. While the operation of the drill jumbo and the water pumps employed for the application of the shotcrete contributes with a 12 %. The concrete itself contributes with another 12 %.

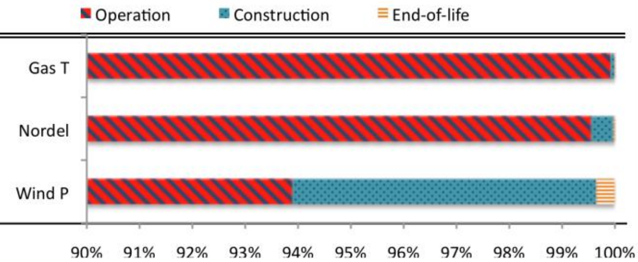
6.4. How are the emissions of greenhouse gases caused and; How can be avoided?

The GHG emissions produced along the life cycle of the pumped storage hydro plant can be separated into two groups. The first is linked to the operational phases, leaving aside the maintenance process, while the second to the construction and dismantling phases and the maintenance process. The GHG emissions at the operational stage are a direct consequence of the generation of electricity feeding the c-d cycle. For all of the three cases assessed, this phase sees the major emission of GHG, followed by the construction phase and then the dismantling phase.

The table 18 presents a benchmark of the GHG emissions for the three cases. When the electricity to run a c-d cycle is generated from a gas turbine plant , the system produces 5 time more GHG that when it is feed by electricity from Nordel mix, and 80 times more than when feed by wind power. On the other hand the GHG emissions produced during the construction and the end-of life phases are obviously the same for the three cases.

Table 18 Contribution to Climate Change throughout the life cycle for the pumped storage plant, comparison between electric generation options, breakdown per life cycle phase

Climate Change per phase FU: 1MJ*Day	CC-Gas Turbine kg CO2-Eq	CC-Nordel Mix kg CO2-Eq	CC-Wind Power kg CO2-Eq
Operation	4.00E-03	5.80E-02	3.23E-01
Construction	2.45E-04	2.45E-04	2.45E-04
End-of-life	1.49E-05	1.49E-05	1.49E-05



The breakdown at figure 18 presents the GHG generated by the construction and fabrication of the main components of the pumped storage hydro plant. During this process the 82% of the total GHG produced are ascribed to the reversible Francis turbine which accounts for 1.19E-03 kgCO2-eq. It is followed by the underground facilities (water tunnels, chambers & access tunnel) representing the 15% with a value of 1.19E-03 kg CO2. Regarding the metals used for the reversible turbine this study's inventory is based on assumptions, an aspect which should be improved in the future. Concerning the underground facilities a considerable amount of the data was generated from assumptions, while several activities and operations that appear to be energy intensive were not included due to a lack of sources, not allowing constructing a more complete inventory.

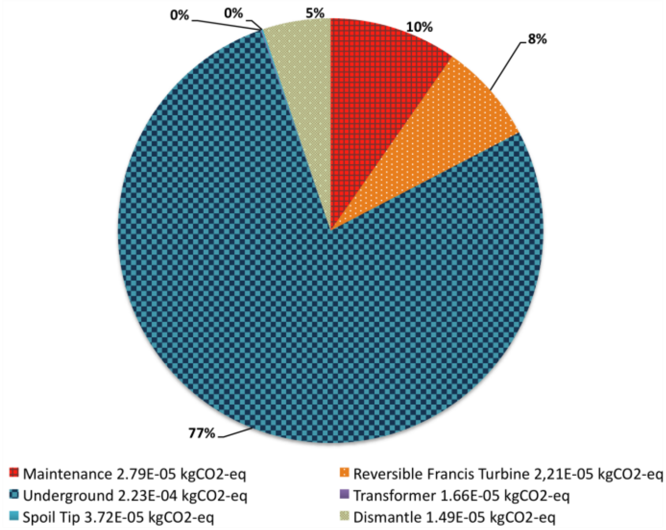


Figure 18 Climate change contribution along the construction, dismantle and maintenance, detail breakdown per main components at the construction phase.

As result the main options for dismantling GHG are to employed wind power at run the c-d cycles during the operational phase. While during the construction and dismantle, there is a possibility that shall be evaluated to the future as is the use of recycled materials to the manufacture of the turbine components and at the support work. Nowadays at least regarding to the manufacture of turbines there is not such a acknowledgement of the potentiality for reducing this emissions by employing recycle materials, this shall be considered in more detail (Dahlhaug, 2011)

6.5. What are the associated land use change effects, emissions of other pollutants and their potential impact?

The land use transformations effects throughout the whole life cycle of the pumped storage plant can be divided into: 1. the impacts caused by construction, maintenance and dismantling of this facility and 2- the impacts from the generation of the electricity technology running the c-d cycle. This differentiation can be applied as well to the other potential impacts.

Most of the contributions to the land uses transformation depend on the electricity generation technologies, as it is illustrated in the table below. An advanced contribution analysis regarding each of the life cycle phase is presented, followed by a more detailed breakdown per components of each phase. A reason why the land use transformation effects are happening during the operational phase is related to the electricity requirements along the whole life time of the pumped storage.

Table 19 Contribution to land use transformation associated to the life cycle of the pumped storage plant, by electricity option.

Land use transformation FU: 1MJ*day	*Gas Turbine at Pumped Storage*			*Nordel at Pumped Storage*			*Wind Power at Pumped Storage*		
	NLT	ALT	ULT	NLT	ALT	ULT	NLT	ALT	ULT
Operation	99.7%	71.5%	86.5%	98.1%	99.4%	94.1%	71.3%	70.2%	94.0%
Construction	0.3%	28.5%	13.5%	1.8%	0.6%	5.9%	27.4%	29.8%	6.0%
End-of-Life	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	1.2%	0.0%	0.0%
Phases	**NLT**	**ALT**	**ULT**	**NLT**	**ALT**	**ULT**	**NLT**	**ALT**	**ULT**
Operation-Electricity Production	78.2%	55.6%	67.7%	76.9%	77.9%	73.7%	55.6%	54.6%	73.6%
Operation- η lost at Pumping mode	21.5%	15.3%	18.7%	21.2%	21.5%	20.3%	15.3%	15.0%	20.3%
Construction- Reversible Francis Turbine	0.2%	25.4%	12.3%	1.4%	0.5%	5.4%	21.4%	26.6%	5.5%
Construction- Underground	0.1%	2.7%	1.2%	0.4%	0.1%	0.5%	6.0%	2.8%	0.5%
Operation- Maintenance	0.0%	0.6%	0.1%	0.0%	0.0%	0.0%	0.5%	0.6%	0.0%
End-of-Life-Dismantle	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	1.2%	0.0%	0.0%
Construction- Spoil Tip	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Construction- Transformer	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%

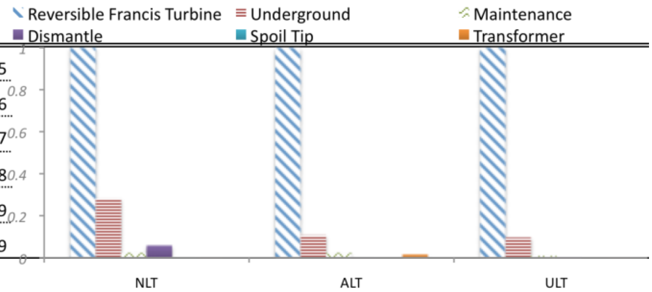
When the plant is run using gas turbine electricity 5.53E-05 m2 of natural land get modified, while wind power plant is responsible for modifying 4.19E-07 m2. The use transformation of agricultural land caused by a pumped storage hydro plant run by wind power and with a lifetime of 100 years is of 3.09E-04m2

By comparing the land use transformations during the maintenance, construction and end-life phases, is possible to observe that the majority of them are attributable to the construction of the reversible Francis turbine, followed by the construction of the underground facilities. The table below presents the total land transformation ascribable to each component of the facility. The values in the graph are normalized against the highest environmental impact

The table below presents the total land transformation in relation with each of the components of the facility. The graph values are normalized against the highest environmental impact

Table 20 Comparison of contribution to land use transformation between the constructions, dismantle and maintenance operations, detail breakdown for the main process and components at the construction phase

Land use trans. FU: 1MJ*day	*NLT* m2	*ALT* m2a	*ULT* m2a
Reversible Francis Turbine	1.26E-07	3.00E-05	1.80E-05
Underground	3.56E-08	3.20E-06	1.73E-06
Maintenance	2.85E-09	6.72E-07	1.60E-07
Dismantle	7.33E-09	1.94E-08	2.82E-08
Spoil Tip	8.20E-11	1.15E-09	2.19E-09
Transformer	5.91E-11	4.55E-07	7.37E-09

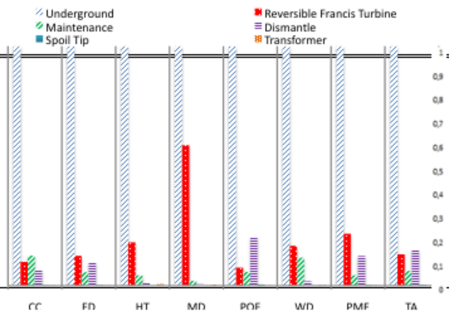


SPA analysis performed for land use transformation has left aside the operational phase while focusing on construction, end of life and maintenance. Regarding agricultural land, the main use transformation occurs at the construction phase, mainly due to the high demand of materials as steel, wood and concrete, and their manufacturing with the subsequent demand for hard coal as fossil fuel and timber (Appendix H)

Along the cradle to grave life cycle of the pumped storage plant the associated environmental impacts are presented in the table 21, this time the focus is on the construction, dismantling and maintenance phases. The underground facilities construction shows the greatest environmental contribution for all the categories, followed by the reversible Francis turbine. The SPA reveals that this is due to the high amount of metal resources that are needed during the construction of these two phases (Appendix H).

Table 21 Environmental impacts associated to the construction, dismantle and maintenance phases at the life cycle of the pumped storage plant, the values at the graph are

Pumped Storage FU: 1MJ*day		Underground	Reversible Francis Turbine	Maintenance	Dismantle	Spoil Tip	Transformer
CC	g CO2-Eq	2.23E-01	2.21E-02	2.79E-02	1.49E-02	3.72E-04	1.66E-04
FD	g oil-Eq	5.32E-02	6.62E-03	2.99E-03	5.21E-03	1.32E-04	5.11E-05
HT	g 1,4-DCB-E	8.06E-02	1.46E-02	3.45E-03	7.58E-04	2.47E-05	5.48E-04
MD	g Fe-Eq	6.26E-02	3.67E-02	1.26E-03	3.63E-04	1.20E-05	2.79E-04
POF	g NMVOC	1.02E-03	7.65E-05	5.83E-05	2.05E-04	4.86E-06	6.89E-07
WD	m3	4.64E-04	7.72E-05	5.43E-05	8.37E-06	2.51E-07	1.08E-06
PMF	g PM10-Eq	4.91E-04	1.06E-04	2.13E-05	6.07E-05	1.41E-06	7.36E-07
TA	g SO2-Eq	8.06E-04	1.05E-04	4.95E-05	1.20E-04	2.84E-06	1.16E-06



6.6. *Discussion*

This thesis has analyzed the overall environmental performance of pumped storage hydro power plant. This study has been based upon the description plans of the construction of Tonstad III by Sira-Kvina. A benchmark of three possible set up for the operational mode of the plant has been performed as part of the analysis. The environmental performance of the system has been evaluated employing a charge discharge approach, where the impacts were calculated from a cradle to grave perspective, developing a detailed description of the materials, energy requirements and other resources employed along the construction, operation and dismantling phases of the plant; the life of the plant has been assumed of 100 years

According to the results obtained the demand of electricity for running up a charge discharge cycle is responsible for almost all the share of the environmental impact. This is mainly because of the facility’s long life span that makes the emissions produced during construction, maintenance and dismantling operation almost insignificant compared to the ones generated by the continuous conversion through the c-d cycle.

6.6.1. Data uncertainty

The data reliability is a challenge for next studies. There are several operations in each of the components of the system that weren't taken into consideration, operations that might have important environmental impacts. This is the case of the ventilation system at the underground construction process, on average is estimated to be around 30% or more of the total cost during the construction of tunnels with a cross-section of 60 m^2 or more (Rønn 1998). The main reason why this was not considered is the lack of inventory data for large scale ventilation system, with the sources found and the Ecoinvent v. 2.2 (2008) database only registering small units of dwellings.

Another aspect that shall be improved regards the calculation of the explosive requirement according to the rock stability index (SPR)(Zare 2007). This index provides the amount of explosives (kg/m3) needed to break the rock to a certain degree of fragmentation. This has direct implications on: how work intensive would be the drilling stage, considering that the diameter to drill is related to the amount of explosive how intensive the crushing process would be needed before hauling and finally on how intensive would be the ventilation process (extraction of fumes) to dissipate the fumes being released after the explosion.

At this point is relevant a further detailed description and data compilation regarding the manufacturing process of the reversible turbine, considering that this is necessarily energy intensive. In relation to the selection of the materials employed for the production of the turbine components several assumptions were made, since the metals actually used were not part of the Ecoinvent v.2.2 (2008) database, the only one employed by the LCA_gui v.13.2 (2009) performed. To avoid this problem in the future it's now possible to use the Idemat database that includes the inventory of most of these metals.

As noted before, this study does not consider the construction and operation of the reservoirs. In the case of Norway while the operation might not have big impacts regarding GHG emissions thanks to the temperature conditions, it certainly has a considerable impact concerning the land requirement. Other environmental impacts occurring at the reservoirs and for which does not exit any impact indicator have to be considered apart.

The table below shows an overall evaluation of the quality of the data employed in the inventory.

Quality of the Life Cycle Inventory

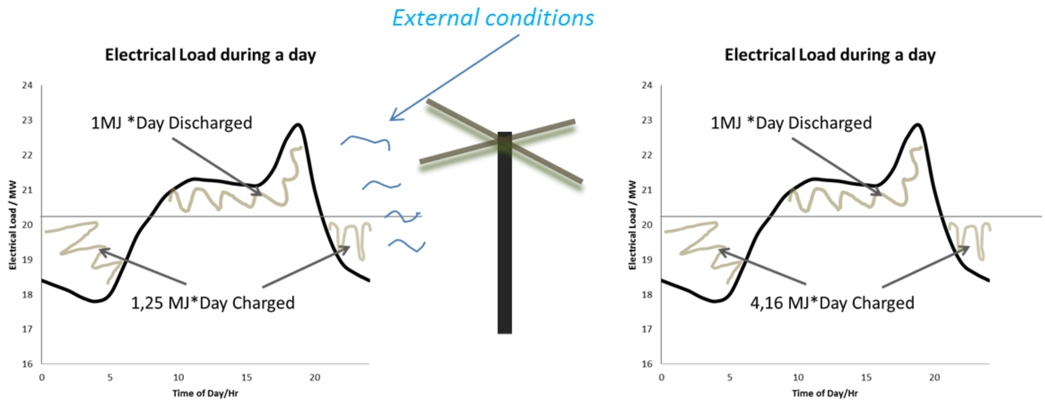
Foreground	*Process*	*Inventory Completness (+)*	*Inventory Uncertainty (-)*	*Quality of Ecoinvent match (+)*	*Overall LCI quality*
Underground	Excavation	Medium	*High*	Low	Low
Main issue: energy intensive process not considered					
Underground	*Muck Removal*	Medium	*Medium*	Low	Low
Main issue: haulage methos is not the proper for the size of the underground construction					
Underground	*Support Work T*	Medium	*Medium*	Low	Medium
Main issue: requierment for first source data, few second source data found					
Underground	*Support Work Ch*	Medium	*Medium*	Low	Medium
Main issue: requierment for first source data, few second source data found					
Underground	*Lining*	Medium	*Medium*	Low	Medium
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Reversible Francis Turbine	*Pressure Shaft*	Low	*Low*	Low	low
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Reversible Francis Turbine	*Spiral Casing*	Low	*Low*	Low	low
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Reversible Francis Turbine	*Covers*	Low	*Low*	Low	low
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Reversible Francis Turbine	*Guide Vanes*	Low	*Low*	Low	low
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Reversible Francis Turbine	*Runner*	Low	*Low*	Low	low
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Reversible Francis Turbine	*Laberynth Seal*	Low	*Low*	Low	Medium
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					
Spoil Tip	*Adequation*	Low	*Low*	Low	Medium
Main issue: requierment for first source data, few second source data found					
Spoil Tip	*Filling*	High	Medium	High	High
Main issue: requierment for first source data, few second source data found					
Transformer	*Remedial Work*	High	High	High	High
Main issue:					
Transformer	*Transformer*	High	High	High	High
Main issue:					
Mantainance	*Man Support Work T & CH*	Medium	*Medium*	Low	Medium
Main issue: requierment for first source data, few second source data found					
End of Life	*Metal Part dIsposal*	Low	*High*	Medium	Low
Main issue: assumption regarding the type of metal emplyed for it construction, no categoires available at Ecoinvent					

6.6.2. Other topics to be considered in future studies (Scenario)

The electrical load along the day varies according to the demand; this demand is highly dependent on the use of electricity occurring at dwellings. This load varies also according to the time of the year, being the requirement higher in winter than during summer. This is drastically evident in a place like Norway, characterized by cold and dark winter, in contrast with sunny and mild summers. In order to supply the energy required to load the production with the demand the generation sources are usually classified into three different load levels (table 8). The classification of the generating technologies along these levels takes into account the cost of electricity produced, the reliability, and the load adjustment capacity.

Regarding the production of the electricity required for running a c-d cycle, gas turbine and the wind power are usually used as spinning reserves at an energy system, while the Nordel mix provides the whole spectrum of several generation technologies loading the daily demand of electricity. Wind power has major issues concerning its lower readability due to the dependency upon external fluctuations (meteorological conditions). As the fault the amount of electricity produced by wind power that goes into the grid usually does not exceed 20% of the total productive capacity (Uchiyama 2007). In this way a pumped storage facility store the extra amount of the energy that is lost and later on during the peak demand it match the demand with the store energy.

Table 22 Set up of the electricity requirement according to the electrical load

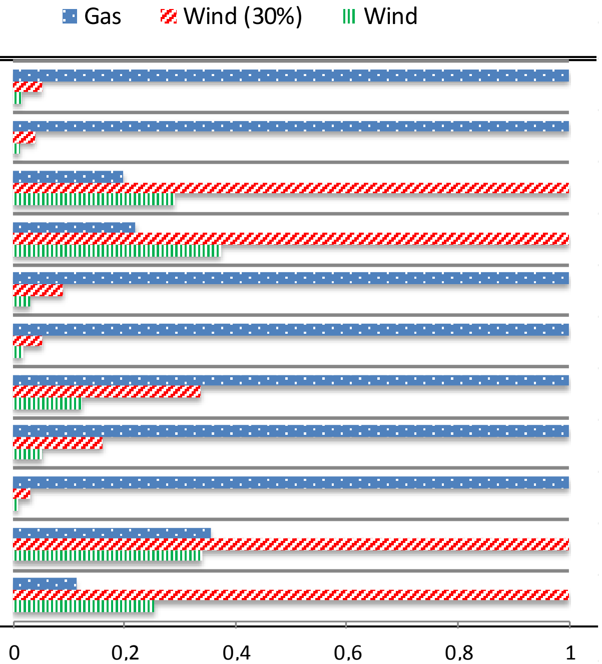


Above are presented the two settings of the pumped storage plant facility run by wind power that have been assessed. The left one is the case the results refer to, where it is assumed that all the electricity produced at a moment goes to the storing system. The second illustrates the case where only a 30 % of the total electricity production enters to the grid, implying an over requirement of a 70% for the production of a certain amount. It means/implies that in order to produce 1MJ* day it's necessary to have a total production of 4,16 MJ , .

At table 23 is presented a comparison of the overall environmental performance throughout the life cycle of the pumped storage facility when is run with electricity produced from a gas plant, when uses wind power electricity considering the two cases above. Even when the electricity is from a wind plant with an overproduction its contribution along the environmental impact categories is smaller for most of the cases. The new electricity input from wind contributes to the metal depletion 2,5 times more than the first case., and 4,5 times more than when the electricity is from a gas plant. Similar trends take place regarding the contribution to human toxicity and land use transformation (agricultural and urban) .

Table 23 Environmental contribution along the life cycle of the pumped storage facility, values normalized against the highest score

Pumped Storage FU: 1MJ*day		*Gas*	*Wind (30%)*	*Wind*
CC	*g CO2-Eq*	3,24E+02	1,68E+01	5,43E+00
FD	*g oil-Eq*	1,29E+02	5,17E+00	1,64E+00
HT	*g 1,4-DCB-Eq*	3,34E+00	1,67E+01	4,86E+00
MD	*g Fe-Eq*	3,31E+00	1,50E+01	5,60E+00
POF	*g NMVOC*	5,94E-01	5,41E-02	1,82E-02
WD	*m3*	8,89E-01	4,68E-02	1,58E-02
PMF	*g PM10-Eq*	1,42E-01	4,81E-02	1,77E-02
TA	*g SO2-Eq*	4,36E-01	7,03E-02	2,33E-02
NLT	*m2*	5,55E-02	1,80E-03	5,92E-04
ALT	*m2a*	1,18E-01	3,33E-01	1,13E-01
ULT	*m2a*	1,46E-01	1,29E+00	3,29E-01



7. Conclusion

This study focuses on building a comprehensive inventory for a pumped storage power plant, as a basis for comparing the performance of the plant when using two different sources of electricity that are usually employed as spinning reserves to produce electricity for supplying the peak demand. Gas turbine and wind power were the two option evaluated, while the Nordel mix was added as a stick parameter. The configuration of the pumped storage plant had a high importance along the assessment, providing new insights regarding components as water turbines and underground tunneling.

The findings of this study allow observing that the environmental impacts occurring along the life cycle of a pumped storage plant are highly determined by the type of electricity that is feeding the system. Considering as the option with lower environmental load the storage of electricity produced by wind power which has an impact of 5,43g-CO2eq to the climate change impact category, 60 times lower than in the case of gas turbine 3,24E+02gCO2-eq. Similar results were obtained in the case when a 30% of the wind power generated was being utilize to run the c-d cycle implying an over requirement of electricity to be produced; the contribution to climate change was of 1,68E+01gCO2-eq, 20 times lower than when gas turbine is employed.

When evaluating the environmental performance of the construction, maintenance and dismantling phases was obtain that the main impact contributions are associated to the use of metals for the construction of the tunnel and the reversible Francis turbine.

The wind power option at first glance has the best overall environmental performance, and considering its high dependency upon external factors, such that the minimum requirement for assuring production and provision of electricity makes the climate change impact increasing in an order of 4 times, but still it remains the best option of the ones evaluated.

The methodology at the base of this study does not leave room for environmental impacts usually taken into account on the environmental assessment of this type of systems. Most of these potential impacts are related to the aquatic biota, as a modification of the frequency of the water flows can imply drastic changes in the conditions needed for the survival and reproduction of several species.

Considering this, the type of study here performed should always be complemented with studies that illustrate the ecological risk associated with the increase of the hydropeaking on the reservoirs.

Even though it took a significative effort to create a detailed inventory for all the phases, the overall impacts from other activities and operations besides the production of electricity are overwhelmed when they are benchmarked.

The main conclusion of this study is that the type of electricity employed for running the pumped storage system would determine the overall impacts assessments, considering this it results that the introduction and employment of more electricity from renewable sources would allow to dismantle GHG gases while producing co-benefits in the reduction of other environmental impacts.

8. References

Anon, Files - ReCiPe. Available at: http://sites.google.com/site/lciarecipe/file-cabinet [Accedido Junio 13, 2011].

Bakken, T., 2011. Environmental impact of pumped storage hydropower plants: Norwegan perspectives. Available at: www.forum-netzintegration.de/.../DUH_Sintef_Bakken_21022011.pdf.

Bauer, C., Bollinger, R. & PSI, 2007. *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries*, Switzerland.

Baumann, H., 2004. *The hitch hiker's guide to LCA : an orientation in life cycle assessment methodology and application*, Lund Sweden: Studentlitteratur.

Bernstein, L. et al., 2007. Climate Change 2007: Synthesis Report. En T. Barker & A. Allali, eds. Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

Brånnfors, S., 2002. *Rock tunneling in Sweden from conception to a completed product*,

Bränström-Noreberg, 1995. *Life cycle for vattenfall´s ekectricity generation*, Sweden. Available at: www.vattenfall.se/.../Life_cycle_assessment_for_Vat_8459698.pdf_17581721.pdf.

Broch, E., 2010. Tunnels and underground works for hydropower projects. Lesson learned in a home country and from project worldwide.

Cagnon, L. & Chamberland, A., 1993. Emissions from hydroelectric reservoirs and comparison of hydroelectricity, natural-gas and oil. *Ambio*, 22.

Cedren & Sintef, 2008. Hydro reaches the Peak (hydropeak) Tasks (A to F). Available at: http://www.cedren.no/LinkClick.aspx?fileticket=rlB_tswnYSY%3D&tabid=3787.

Chen, H., 1993. *Pumped Storage. In Davis´Handbook of applied Hydraulics* 4o ed., New York N.Y.: McGraw HIll.

Dahlhaug, O., The choise of materials for turbines. Available at: http://www.ivt.ntnu.no/ept/fag/tep4200/innhold/The%20choice%20of%20materials.pdf.

Dahlhaug, O.G., 2011. Materials choice for water turbines.

Deffeyes, K., 2010. Hubbert's Peak, Home. Available at: http://www.princeton.edu/hubbert/ [Accedido Junio 12, 2011].

Dimitrios, K., 2008. Tunneling and tunnels mechanics: a regional approach to tunneling.

Dones, R. et al., 2007. Life cycle inventories of energy system: Result for current system in switzerland and other UCTE countries. Available at: http://www.ecolo.org/documents/documents_in_english/Life-cycle-analysis-PSI-05.pdf.

Dubreuil, A., Gaillard, G. & Müller-Wenk, R., 2006. Key Elements in a Framework for Land Use Impact Assessment Within LCA (11 pp) L. Milà, ed. *The International Journal of Life Cycle Assessment*, 12(1), pág.5-15. Available at: [Accedido Junio 14, 2011].

Electricity Storage Association, 2009. Electricity Storage Association - power quality, power supply: Technical Papers. Available at: http://www.electricitystorage.org/ESA/technical_papers/ [Accedido Enero 10, 2011].

EU & ESMIG, 2008. the 20-20-20 goals — Esmig. *European Smart metering industry group*. Available at: http://www.esmig.eu/smart-metering/the%2020-20-20%20goals [Accedido Junio 12, 2011].

Evans, S., 2011. BBC News - Germany: Nuclear power plants to close by 2022. Available at: http://www.bbc.co.uk/news/world-europe-13592208 [Accedido Junio 10, 2011].

Farre, C., 2007. Hydroelectric Reservoirs - the Carbon Dioxide and Methane Emissions of a «Carbon Free» Energy Source. Available at: www.up.ethz.ch/education/.../Farrer_rev_termpaper_hs07.pdf.

Friedrick, R. & Marheineke, T., 1994. Life cycle analysis of electricity Systems: methods and results:

Fry, P., Gabler, W. & Hartmann, O., 1969. Pumped Storage as standby for nuclear power plant.

Gagnon, L. & Uchiyama, Y., 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy*, 30(14), pág.1267-1278.

Gagnon, L. & Vate, van de, 1997. Greenhouse gas emissions from hydropower The state of research in 1996. *Energy Policy*, 25(1), pág.7-13. Available at: [Accedido Junio 12, 2011].

Gagnon, L., Bélanger, C. & Uchiyama, Y., 2002. Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energy Policy*, 30(14), pág.1267-1278. Available at: [Accedido Junio 14, 2011].

Godish, T., 1997. *Air Quality* 3o ed., New York N.Y.: Lewis Publisher's.

Goedkoop, M. et al., 2009. *ReCipe 2008- A life cycle impact assessment method with compromises harmonized category indicators at the midpoint and the endpoint level*, Pre Consultants, CML, RUN, RIVM. Available at: http://www.lcia-recipe.net/.

Houghton, J., 2009. *Global warming : the complete briefing* 4o ed., Cambridge: Cambridge University Press.

Huggins, R.A., 2010. *Energy Storage*, Boston, MA: Springer US. Available at: http://www.springerlink.com/index/10.1007/978-1-4419-1024-0 [Accedido Junio 9, 2011].

Husebye, S. ed., 2002. Environmental and Health Impact of electricity Generation- a comparison of the environmental impact of hydropower with those of other generation technologies. Available at: www.ieahydro.org/reports/ST3-020613b.pdf.

IEA, 2009. World Energy Outlook 2009. Available at: http://www.iea.org/weo/index.asp [Accedido Enero 27, 2011].

Indecol & NTNU, 2009. *LCA_GUI*, Norway: NTNU.

International Energy Agency, 2010. World Energy Outlook 2010. Available at: http://www.iea.org/weo/index.asp.

IPCC, 2007. *Climate change 2007 Mitigation of Climate Change*, UNEP.

ISO, 2006. Environmental management- Life Cycle Assessment- Principle and framework. Available at: http://www.iso.org/iso/catalogue_detail?csnumber=37456.

Johansen, J., 2000. *Modern trends in tunneling and blast design*,

Jorge, R., 2011. Transformer 560 MVA transformer BBA.

Kjølle, A., 2001. *Hydropower in Norway Mechanical Equipment*, Norwegian University of Science and Technology. Available at: www.magnu.polymtl.ca/contenu/ressources/docDivers/.../Turbines101.pdf.

Levine, J. & Barnes, F., 2011. *Large Energy Storage System Handbook* Boulder Colorado., Boca Raton: CRC Press. Available at: https://webmail.ntnu.no/horde2/index.php?url=https%3A%2F%2Fwebmail.ntnu.no%2Fhorde2%2F [Accedido Junio 9, 2011].

Majeau-Bettez, G., Hawkins, T.R. & Strømman, A.H., 2011. Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles. *Environmental Science & Technology*, 45(10), pág.4548-4554. Available at: [Accedido Junio 14, 2011].

Naish, C., McCubbin, I. & Edberg, O., 2008. *Outlook of energy storage technologies*, Brussels. Available at: http://www.storiesproject.eu/?secid=6.

Panthi, K., 2011. Introduction to Drill and Blast.

Portland Bolt & manufacturing, Inc., 2011, Anchor Rods | Portland Bolt. Available at: http://www.portlandbolt.com/products/rods/anchor_rod.html [Accedido Junio 18, 2011].

Raquel, J., 2011. Life Cycle Inventory- Transformer.

Rønn, P.-E., 1998. Drill and Blast-Extremely long rounds.

Rosenberg, D., Bodaly, R. & Usher, P., 1995. Environmental and social impacts of large scale hydroelectric development: who is listening? *Global Environmental Change*, 5(2), pág.127-148. Available at: [Accedido Junio 12, 2011].

Schuller, O. & Albrecht, S., 2008. Setting up life cycle Models for the environmental analysis of hydropower generation, considering technical and climatic boundary conditions. Available at: www.lcacenter.org/LCA8/presentations/307.pdf.

Sherlock, P., Greenslade, W. & Robert, C., 1971. Environmental studies for a pumped storage-nuclear station power complex. En *Pumped storage development and it´s environmental effect*. Wisconsin, United State.

Sira-Kvina, 2001. Hovedmagasiner - SiraKvina. Available at: http://www.sirakvina.no/Prosjekter-og-anlegg/Hovedmagasiner/ [Accedido Junio 15, 2011].

Sira-Kvina, 2007. Installation in Tonstad power station with the possibility of pumping. Available at: http://www.sirakvina.no/Prosjekter/Tilleggsinstallasjon-i-Tonstad/.

Smil, V., 2006. Energy at the Crossroads. En *Conference on Scientific Challenges for Energy research*. Scientific Challenges fro Energy Research. Paris.

Statkraft & Ostfold, 2006. EPD Hydroelectricity. Available at: http://www.nho.no/files/NEPD010stkrEN_1.pdf.

Steele & Smokorowski, 2000. Review of literature related t the downstream ecological effects of hydroelectric power generation. Available at: www.dfo-mpo.gc.ca/Library/251234.pdf.

Swiss Centre for Life Cycle Inventories, 2008. *Ecoinvent v2.2*, Hamburg GmbH: Swiss Centre for Life Cycle Inventories. Available at: http://www.ecoinvent.ch/.

Thohne, E. & Kallenbach, U., 1988. Risikovergleiche für die Stromerzeugung.

Tokyo Electric Power Co., 2011. *Benefits due to power generation- Large Pumped Storage Power Plants, Japan*, Available at: www.ieahydro.org/.../Annex_VIII_CaseStudy1102_LargeScalePS_Japan.pdf.

Toshiba Co., 1985. Hydraulics Turbines-Toshiba International Corporation. Available at: www.tic.toshiba.com.au/product_brochures_and.../hydrotb.pdf.

Troelstrup, N.H. & Hergenrader, G.L., 1990. Effect of hydropower peaking flow fluctuations on community structure and feeding guilds of invertebrates colonizing artificial substrates in a large impounded river. *Hydrobiologia*, 199(3), pág.217-228. Available at: [Accedido Junio 27, 2011].

TU Delft, IDEMAT Home. Available at: http://www.idemat.nl/ [Accedido Junio 29, 2011].

Uchiyama, Y., 2007. Life cycle assessment of renewable energy generation technologies. *IEEJ Transactions on Electrical and Electronic Engineering*, 2(1), pág.44-48.

Varun, Prakash, R. & Bhat, I.K., 2010. Life Cycle Energy and GHG Analysis of Hydroelectric Power Development in India. *International Journal of Green Energy*, 7(4), pág.361-375.

Vetz, C.J., 1971. Environmental aspect of pumped storage development reason or emotion. En *Pumped storage development and it´s environmental effect*. Wisconsin, United State: The University of Wisconsin-Milwaukee.

Vold, M. & Magnussen, K., 1996. *Integrating economic Valuation to Life cycle Assessment for sustainable Energy Production*, Norway: Stiftelsen Østfoldrskning. Available at: http://www.ostfoldforskning.no/uploads/dokumenter/publikasjoner/311.pdf.

Vold, M., Erstad, E. & Magnussen, K., 1996. *LCA od Norwegian Hydroelectricity-Summary Report*, Fredrikstad, Norway: Øsfold Researh Foundation. Available at: http://www.ostfoldforskning.no/uploads/dokumenter/publikasjoner/311.pdf.

Walseth, E.C., 2011. Description of Francis Reversible Turbines.

WIlson, E. & Gwynn, J., 1971. The use of tidal energy to augment pumped storage. *Pumped Storage Development and its environmental effects*.

Zare, S., 2007. *Prediction Model and Simulation Tool for time and cost of drill and blast Tunneling*. Norway: NTNU.

I. Appendix A

Calculation of energy lost at pumping mode

$$energy\ lost = \frac{1}{\eta_{turbine} * \eta_{pump}} - 1$$

$$energy\ lost = \frac{1}{98\% * 80\%} - 1$$

$$energy\ lost = 27{,}5\%$$

Calculation of the environmental load associated with the construction and the dismantle process of the Pumped storage hydro plant facility. This load factor distributes linearly to each unit output, being for this assessment the define functional unit (1MJ*day)

$$load\_factor = \frac{FU}{total\_production\_over\_lifetime}$$

$$l\_f = \frac{FU}{\mu_{year}\tau_{life}}$$

Where the annual production μ_{year} is 365 MJ*day, and the life time τ_{life} is 100 years

$$l\_f = \frac{1MJ*day}{365\, {}^{MJ*day}\!/_{yr} * energy\_capacity\_install * facility\_capacity}$$

$$l\_f = \frac{1MJ*day}{365\, {}^{MJ*day}\!/_{yr} * 100\,yr * 0,8\% * 1000\,MW * 3600\, {}^{sec}\!/_{hr} * {}^{24hr}\!/_{day}}$$

$$l\_f = 3,3963E-13$$

II. *Appendix B*

Value	Units	Description	Source
		Main Parameters & assumptions Undergound Construction	
1500000	tons	Muck remove	Sira-kvina Master plan
0,75	%	Around 75% of total works is at tunnel	Interview
0,25	%	Around 60& of total work is at chamber	Interview
120	m	Crosssection	Sira-kvina Master plan
350	m3/cycle	Volume of muck D&B after each cycle	Interview
0,5	#/m3	# of Drill rods requires per m3 of muck excavated	Interview
3	[cycles/day]	# number of cycles taking place per day of work	Interview
2867	kg/m3	Average density of gneiss rock muck	S http://www.simetric.co.uk/si_materials.htm
3,88	kg/m	Weight of a drillrod unit per meter	S
8,5	m	Length of drill rods used at construction	S
1,9	m3/ in*kg	SIA standard for Air Supply after blasting required at excav	Reference
18	min/cycle	average length of break after D&B phase	Reference
2,25	kg/m3	Amount of explosive required per m3 D&B at excavation	Interview
6600	kw	Jumbo drill Nominal diesel consumption	Reference
6	m3/kw*min	Air consumption by excavation and loading machines for (	Reference
3	hr/cycle	average length of D&B cycle	Interview
2	[m3/min]	Min air requirement per person at excavation facility	Reference
1	units	Machines	Assumption
1113,15	km	Distance between London and Kvinasdal Ports (water)	Reference
251	km	Distance between Hearthcote and London (land)	Reference
60	km	Distance between Kvinasdal and Tonstad (land)	Reference
7480	kg/m3	Rock bolts Stainless steel density used	Assumption
2,88	m	Average length of drill whole at rock bolt installation	Assumption
0,00255	m	Rockbolt radios (cylindrical shape)	Reference
450	kg/m3	Shotcrete used at lining at rock bolt installation density	Interview
12,5	km	Tunnel length being excavated	Sira-kvina Master plan
28	tons	Lorry capacity employed, data from Ecoinvent	Ecoinvent
0,02	%	Average amount of drill rods that need maintenance after	Interview
9	#	Number of times that tunnel is dewater for maintenance (	Interview
0,5	m	thickness of shotcrete lining	Assumption
213	km	Distance between Møsh... until Tonstad (land)	Reference
730	km	Distance between Munich and Bremen (land)	Reference
2,5	m	Radios of Pressure shaft	Assumption
0,5	m	Thickness of pressure shaft tunnel	Assumption

III. Appendix C

Machine	Energy consumption (MJ)	Air consumption for combustion (m3/min)
Jumbo drill	974338	1320
Skid steer -(wheel loader)	Ecoinvent v2,2	810
Crusher	Ecoinvent v2,2	255
Shotcrete pump	914284	240
Concrete Trucl (lorry 28t)	Ecoinvent v2,2	240
Mobile pump	914284	240
Truck (lorry 28)	Ecoinvent v2,2	960
Ventilation per stage Underground construction	***Air requierement (m3)***	***Sources***
Excavation	1,26E+12	Calculation fron assumptions and information
Muck Removal	2,35184E+12	
Support Work tunnnel	3,5621E+11	
Support Work chamber	1,18737E+11	
Linning	9,71967E+23	

Ventilation per stage Underground construction	emmission limit of 10 mg/m3	Sources
Machines for excavation & loading [m3]/[kW min]	3	Swiss atandar SIA 196 British standard BS6164 (Betellini,2005)
Machines for Mucking and concreting (shotcrete) [m3]/[kW min]	2	

Mucking Information	***info***	***source***
Dumper Capacity (t)	35	(Zare,2007)
Lorry Capacity (t)	28	(Ecoinvent v2.2)
Total cycles (#)	1710	
Muck Remove/cycle (t)	877,193	
Distance excaveted/cycle (m)	2,5	Cal from Underground Cons Info
Total Trips to remove muck (#)	1,250E+07	
Total distance (km)	7,832E+05	
Total (tkm)	2,741E+07	

[21]

Tunnel lining (shotcrete)	***info***	***source***
Average of percentage lined (%)	3	(Broch, 2010)
Shotcre water/ concrete ratio	0,4	(Panthi,2011)
Concrete (m3)	7,402E+05	Cal from Underground Cons Info
Water	1,332E+02	
Thickness (m)	0,5	(Panthi,2011)
Pressure Shaft lining (shotcrete)	***info***	***source***
Average of percentage lined (%)	3	(Broch, 2010)
Shotcre water/ concrete ratio	0,4	(Panthi,2011)
Concrete (m3)	7,402E+05	Cal from Underground Cons Info
Water (kg)	1,332E+02	
Thickness (m)	0,5	(Panthi,2011)

[21] *Main data and calculation of the total amount of tones and km*

IV. Appendix D

Main Parameters & Assumption Reversible Francis Turbine	Value	Units	Source
Distance between Sarphory to Tonstad	408	km	Reference
Percentage of Carbon Steel used at Spiral Casing	50	%	Dahlhaug,2011
Installation capacity of at Tonstad	560	MW	Sira-kvina Master plan
Weight of spiral casting per MW capacity	0,3	tons/MW	Reference/Interview
Fraction of the weight of Spiral Casting at turbine	0,5	%	Dahlhaug,2011
Percentage of High Quality Strength steel used at Covers	0,5	%	Dahlhaug,2011
Fraction of weight of Guide vanes at turbine	0,05	%	Dahlhaug,2011
Percentage of Stainless steel at Guide Vanes	1	%	Dahlhaug,2011
Fraction of weight of Runner at Reversible Francis Turbine	0,13	%	Dahlhaug,2011
Percentage of Stainless Steel at Runner	1	%	Dahlhaug,2011
Fraction on weight of labyrinth at Reversible Francis turbine	0,2	%	Dahlhaug,2011
Percentage of Carbon Steel used at Spiral Casing	0,25	%	Dahlhaug,2011
Percentage of Staimless steel used at Spiral Casing	0,25	%	Dahlhaug,2011
Percentage of High Quality Strength used at Spiral Casing	0,25	%	Dahlhaug,2011
Percentage of Carbon Steel used at Spiral Casing	0,25	%	Dahlhaug,2011

V. *Appendix E*

Detail Life Cycle Inventory Table

		Activity	Per Pumped Storage	Unit
Underground	Excavation	Blast Process	1,13E+06	*kg*
		Jumbo Drill-rods	5,56E+05	*kg*
		Ventilation at Construction	3,12E+03	*units*
		Crush of muck before hauling	1,13E+09	*kg*
		Jumbo Drill Diesel Consumption	9,74E+05	*MJ*
		Removal of muck	3,92E+05	*m3*
		Transport, workers	1,03E+04	*tkm*
		Transport, Ferry	3,15E+02	*tkm*
		Transport, lorry	8,81E+04	*tkm*
	Muck Removal	Transport, lorry (haulage)	2,74E+07	*tkm*
		Ventilation at Construction	6,99E+06	*units*
		Charging Muck to Trucks	9,74E+05	*m3*
	Support Work T	Rock bolts [total]	1,28E+05	*kg*
		Gouted Shotcrete [total]	2,06E+02	*m3*
		Water at Shotcrete	3,71E+04	*kg*
		Ventilation at Construction	8,83E+02	*units*
		Transport, lorry (Mixer) & (Bolts & Concrete from man	1,22E+05	*tkm*
		Transport, Ferry (bolts)	7,61E+04	*tkm*
		Shotcrete &mobile water pump diesel consumption	1,37E+06	*MJ*
	Support Work Ch	Rock bolts	1,61E+08	*kg*
		Grouted Shotcrete	1,03E+02	*m3*
		Water at Shotcrete	9,93E+04	*kg*
		Ventilation at Construction	2,94E+02	*units*
		Transport, lorry (Mixer) & (Bolts & Concrete from man	1,27E+08	*tkm*
		Transport, Ferry (bolts)	9,56E+07	*tkm*
		Shotcrete &mobile water pump diesel consumption	4,57E+05	*MJ*
	Lining	Shotcrete	7,40E+05	*m3*
		Water at Shotcrete	1,33E+02	*kg*
		Ventilation at Construction	2,41E+14	*units*
		Transport, lorry (Mixer) & (Concrete from manufacture	4,33E+08	*tkm*

Detail Life Cycle Inventory Table

		Activity	Per Pumped Storage	Unit
Reversible Francis Turbine	*Pressure Shaft*	Stainless steel	*6,52E+08*	*kg*
		Transport, lorry	*5,32E+08*	*tkm*
	Spiral Casing	Carbon Steel	*7,20E+04*	*kg*
		Stainless steel	*7,20E+04*	*tkm*
		Transport, lorry	*5,88E+04*	*kg*
	Covers	High Strength Microalloyed Steel& Stainless steel	*1,83E+04*	*kg*
		Transport, lorry	*7,48E+03*	*tkm*
	Guide Vanes	Stainless steel	*1,31E+04*	*kg*
		Transport, lorry	*5,34E+03*	*tkm*
	Runner	Stainless steel	*3,40E+04*	*kg*
		Transport, lorry	*1,92E+04*	*tkm*
	Laberynth Seal	carbon steel	*1,31E+04*	*kg*
		high strength microalloyed steel & stainless steel	*2,62E+04*	*kg*
		heat treatment steel	*1,31E+04*	*kg*
		0,000	*1,31E+04*	*kg*
		Transport, lorry	*2,14E+04*	*tkm*
Spoil Tip	*Adequation*	Spoil Tip adequation (ersbekke)	*5,25E+06*	*kg*
	Filling	Transport, lorry(dumper) (Homstrøl, & Sirdal into ersbe	*1,10E+06*	*tkm*
		Filling (Homstrøl, & Sirdal into ersbekken)	*1,50E+06*	*m3*
	Remedial Work	Spoil Tip adequation	*9,60E+02*	*kg*
Transformer	*Transformer*	Steel	*5,36E+04*	kg
		Copper	*4,00E+04*	kg
		Steel recycle	*9,96E+04*	kg
		Wood	*1,50E+04*	kg
		Transport	*8,73E+04*	tkm

			Activity	Process at Ecoinvent	Per Pumped	Unit
Mantainance	Man Support Work Ph		Support Work Tunnel	concrete	*1,67E+04*	*m3*
				tap water	*6,67E+03*	*kg*
			Support Work Chamber	concrete,	*4,47E+04*	*m3*
				tap water	*1,79E+04*	*kg*
	Man Lining		Lining	concrete,	*1,33E+05*	*m3*
				tap water,	*2,40E+01*	*kg*
	Reversible Francis Turbine		Guide Vanes	chromium steel 18/8	*2,62E+04*	*kg*
				Transport, lorry 28t	*1,07E+04*	*tkm*
			Runner	chromium steel 18/8,	*6,81E+04*	*kg*
				Transport, lorry 28t	*3,85E+04*	*tkm*
		Man Transformer	Transformer	chromium steel 18/8	*1,07E+05*	*kg*
				copper product	*7,99E+04*	*kg*
				steel, electric	*1,99E+05*	*kg*
				wood wool,	*3,00E+04*	*kg*
				Transport, lorry 28t	*1,75E+05*	*tkm*

Detail Life Cycle Inventory Table				
		Activity	**Per Pumped Sto**	**Unit**
Enf-of-Life	Dis Excavation	Jumbo Drill rods	5,56E+05	kg
	Dis Pressure Shaft	Pressure Shaft	6,52E+08	kg
	Dis Spiral Casing	Spiral Casing	1,44E+05	kg
	Dis Covers	Covers	1,83E+04	kg
	Dis Guide Vanes	Guide vanes	3,93E+04	kg
	Dis Runner	Runner	1,02E+05	kg
	Dis Laberynth	Labyrinth Seal Seal	8,68E+04	kg
	Dis Transformer	Transformer	6,25E+05	kg

VI. Appendix F

	Gas Turbine at Pumped Storage FU 1 MJ * Day LC-Phases							
	Operation-Electricity Production	Operation-Lost at Pumping mode	Cons-Reversible Francis Turbine	Construction-Underground	Operation-Maintenance	End-of-Life-Dismantle	Construction-Spoil Tip	Construction-Transformer
CC	78.05%	21.50%	0.37%	0.07%	0.01%	0.00%	0.00%	0.00%
FD	78.14%	21.53%	0.28%	0.04%	0.00%	0.00%	0.00%	0.00%
HT	58.07%	16.00%	23.38%	2.42%	0.10%	0.02%	0.00%	0.02%
MD	30.34%	8.36%	59.35%	1.89%	0.04%	0.01%	0.00%	0.01%
POF	77.67%	21.40%	0.71%	0.17%	0.01%	0.03%	0.00%	0.00%
WD	77.99%	21.49%	0.47%	0.05%	0.01%	0.00%	0.00%	0.00%
PMF	74.93%	20.64%	4.02%	0.35%	0.01%	0.04%	0.00%	0.00%
TA	77.19%	21.27%	1.31%	0.19%	0.01%	0.03%	0.00%	0.00%
NLT	78.16%	21.53%	0.23%	0.06%	0.01%	0.01%	0.00%	0.00%
ALT	55.59%	15.32%	25.42%	2.71%	0.57%	0.02%	0.00%	0.38%
ULT	67.71%	18.65%	12.33%	1.18%	0.11%	0.02%	0.00%	0.01%
Average	*68.53%*	*18.88%*	*11.62%*	*0.83%*	*0.08%*	*0.02%*	*0.00%*	*0.04%*

	Nordel at Pumped Storage FU 1 MJ * Day LC-Phases							
	Operation-Electricity Production	Operation-Lost at Pumping mode	Cons-Reversible Francis Turbine	Construction-Underground	Operation-Maintenance	End-of-Life-Dismantle	Construction-Spoil Tip	Construction-Transformer
CC	76.48%	21.07%	2.01%	0.37%	0.05%	0.02%	0.00%	0.00%
FD	76.29%	21.02%	2.30%	0.34%	0.02%	0.03%	0.00%	0.00%
HT	74.54%	20.54%	4.43%	0.46%	0.02%	0.00%	0.00%	0.00%
MD	25.37%	6.99%	65.49%	2.09%	0.04%	0.01%	0.00%	0.01%
POF	75.01%	20.67%	3.32%	0.80%	0.05%	0.16%	0.00%	0.00%
WD	77.96%	21.48%	0.50%	0.06%	0.01%	0.00%	0.00%	0.00%
PMF	73.07%	20.13%	6.18%	0.53%	0.02%	0.07%	0.00%	0.00%
TA	74.98%	20.66%	3.73%	0.53%	0.03%	0.08%	0.00%	0.00%
NLT	76.92%	21.19%	1.39%	0.39%	0.03%	0.08%	0.00%	0.00%
ALT	77.95%	21.48%	0.50%	0.05%	0.01%	0.00%	0.00%	0.01%
ULT	73.71%	20.31%	5.41%	0.52%	0.05%	0.01%	0.00%	0.00%
Average	*71.12%*	*19.59%*	*8.66%*	*0.56%*	*0.03%*	*0.04%*	*0.00%*	*0.00%*

	Wind Power at Pumped Storage FU 1 MJ * Day LC-Phases							
	Operation-Electricity Production	Operation-Lost at Pumping mode	Cons-Reversible Francis Turbine	Construction-Underground	Operation-Maintenance	End-of-Life-Dismantle	Construction-Spoil Tip	Construction-Transformer
CC	57.34%	15.80%	21.97%	4.10%	0.51%	0.27%	0.01%	0.00%
FD	58.34%	16.07%	21.84%	3.24%	0.18%	0.32%	0.01%	0.00%
HT	64.43%	17.75%	16.06%	1.66%	0.07%	0.02%	0.00%	0.01%
MD	49.98%	13.77%	35.10%	1.12%	0.02%	0.01%	0.00%	0.00%
POF	54.63%	15.05%	23.25%	5.59%	0.32%	1.13%	0.03%	0.00%
WD	55.16%	15.20%	26.29%	2.94%	0.34%	0.05%	0.00%	0.01%
PMF	50.46%	13.90%	32.38%	2.78%	0.12%	0.34%	0.01%	0.00%
TA	55.88%	15.40%	24.52%	3.46%	0.21%	0.52%	0.01%	0.00%
NLT	55.55%	15.31%	21.38%	6.02%	0.48%	1.24%	0.01%	0.01%
ALT	54.57%	15.03%	26.55%	2.83%	0.59%	0.02%	0.00%	0.40%
ULT	73.64%	20.29%	5.48%	0.52%	0.05%	0.01%	0.00%	0.00%
Average	*57.27%*	*15.78%*	*23.17%*	*3.11%*	*0.26%*	*0.36%*	*0.01%*	*0.04%*

VII. Appendix G

Gas Turbine at Pumped Storage FU 1JMJ *Day LC-Phases	CC	FD	HT	MD	POF	WD	PMF	TA	NLT	ALT	ULT
Operation	99.6%	99.7%	74.2%	38.7%	99.1%	99.5%	95.6%	98.5%	99.7%	71.5%	86.5%
Construction	0.4%	0.3%	25.8%	61.3%	0.9%	0.5%	4.4%	1.5%	0.3%	28.5%	13.5%
End-of-Life	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Phases	**CC**	**FD**	**HT**	**MD**	**POF**	**WD**	**PMF**	**TA**	**NLT**	**ALT**	**ULT**
Operation-Electricity Production	78.0%	78.1%	58.1%	30.3%	77.7%	78.0%	74.9%	77.2%	78.2%	55.6%	67.7%
Operation-η lost at Pumping mode	21.5%	21.5%	16.0%	8.4%	21.4%	21.5%	20.6%	21.3%	21.5%	15.3%	18.7%
Construction-Reversible Francis Turbine	0.4%	0.3%	23.4%	59.3%	0.7%	0.5%	4.0%	1.3%	0.2%	25.4%	12.3%
Construction-Underground	0.1%	0.0%	2.4%	1.9%	0.2%	0.1%	0.3%	0.2%	0.1%	2.7%	1.2%
Operation-Maintenance	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%	0.1%
End-of-Life-Dismantle	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Construction-Spoil Tip	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Construction-Transformer	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%

Nordel at Pumped Storage FU 1JMJ *Day LC-Phases	CC	FD	HT	MD	POF	WD	PMF	TA	NLT	ALT	ULT
Operation	97.6%	97.3%	95.1%	32.4%	95.7%	99.4%	93.2%	95.7%	98.1%	99.4%	94.1%
Construction	2.4%	2.6%	4.9%	67.6%	4.1%	0.6%	6.7%	4.3%	1.8%	0.6%	5.9%
End-of-Life-Dismantle	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%
Phases	**CC**	**FD**	**HT**	**MD**	**POF**	**WD**	**PMF**	**TA**	**NLT**	**ALT**	**ULT**
Operation-Electricity Production	76.5%	76.3%	74.5%	25.4%	75.0%	78.0%	73.1%	75.0%	76.9%	77.9%	73.7%
Operation-η lost at Pumping mode	21.1%	21.0%	20.5%	7.0%	20.7%	21.5%	20.1%	20.7%	21.2%	21.5%	20.3%
Construction-Reversible Francis Turbine	2.0%	2.3%	4.4%	65.5%	3.3%	0.5%	6.2%	3.7%	1.4%	0.5%	5.4%
Construction-Underground	0.4%	0.3%	0.5%	2.1%	0.8%	0.1%	0.5%	0.5%	0.4%	0.1%	0.5%
Operation-Maintenance	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
End-of-Life-Dismantle	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.1%	0.1%	0.1%	0.0%	0.0%
Construction-Spoil Tip	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Construction-Transformer	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Wind Power at Pumped Storage FU 1MJ * Day LC-Phases	CC	FD	HT	MD	POF	WD	PMF	TA	NLT	ALT	ULT
Operation	73.6%	74.6%	82.3%	63.8%	70.0%	70.7%	64.5%	71.5%	71.3%	70.2%	94.0%
Construction	26.1%	25.1%	17.7%	36.2%	28.9%	29.2%	35.2%	28.0%	27.4%	29.8%	6.0%
End-of-Life-Dismantle	0.3%	0.3%	0.0%	0.0%	1.1%	0.1%	0.3%	0.5%	1.2%	0.0%	0.0%

Life-Cycle Phases	CC	FD	HT	MD	POF	WD	PMF	TA	NLT	ALT	ULT
Operation-Electricity Production	57.3%	58.3%	64.4%	50.0%	54.6%	55.2%	50.5%	55.9%	55.6%	54.6%	73.6%
Operation- η lost at Pumping mode	15.8%	16.1%	17.8%	13.8%	15.1%	15.2%	13.9%	15.4%	15.3%	15.0%	20.3%
Construction- Reversible Francis Turbine	22.0%	21.8%	16.1%	35.1%	23.2%	26.3%	32.4%	24.5%	21.4%	26.6%	5.5%
Construction- Underground	4.1%	3.2%	1.7%	1.1%	5.6%	2.9%	2.8%	3.5%	6.0%	2.8%	0.5%
Operation- Maintenance	0.5%	0.2%	0.1%	0.0%	0.3%	0.3%	0.1%	0.2%	0.5%	0.6%	0.0%
End-of-Life-Dismantle	0.3%	0.3%	0.0%	0.0%	1.1%	0.1%	0.3%	0.5%	1.2%	0.0%	0.0%
Construction- Spoil Tip	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Construction- Transformer	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%

VIII. Appendix H

Structural path analysis calculated for the life cycle of the pumped storage plant excluding the operational phases. With the aim of getting a better grasp of how the environmental impacts of the construction, dismantle and maintenance phases is distributed along the value chain of the pumped storage plant.

agricultural land occupation/ RER/ (H)

ABSOLUT	***RELATIVE t***	***SEQUENCE:***								
5,63E-07	11,47256	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	pig iron, at plant/ GLO/ kg	hard coal	hard coal mix,
4,65E-07	9,4817552	Operation	Maintenance	Maintenance T	wood wool boards, (	wood wool,	industrial residue wood,	round wood, softwood, debar	round wood,	softwood,
4,31E-07	8,7910743	Operation	Construction	Transformer	Transformer	wood chips,	industrial residue wood,	industrial residue wood, hard	round wood,	softwood,
2,76E-07	5,6295586	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	pig iron, at plant/ GLO/ kg	hard coal	hard coal mix,
2,73E-07	5,5643467	Operation	Construction	Underground	Lining	concrete, exacting	portland cement,	clinker, at plant/ CH/ kg	hard coal	hard coal
1,81E-07	3,6961749	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	pig iron, at plant/ GLO/ kg	hard coal	hard coal,
1,6E-07	3,26634	Operation	Construction	Underground	Lining	concrete, exacting,	concrete mixing plant	building, multi-storey/ RER/ m	sawn timber,	sawn timber,
1,16E-07	2,3558144	Operation	Construction	Underground	Lining	concrete, exacting,	portland cement,	cement plant/ CH/ unit	building,	sawn timber
1,06E-07	2,1556661	Operation	Construction	Underground	Support Work Ch	reinforcing steel	steel, electric,	iron scrap, at plant/ RER/ kg	scrap preparatic	building, multi-storey

STRUCTURAL PATH ANALYSIS Pumped Storage Facilities (construction-maintenance and end-of live)

climate change/ GLO/ (H)

ABSOLUTE	***RELATIVE t***	***SEQUENCE:***						
8,338E-05	28,944741	Operatior	Construction	Underground	Lining	concrete, exacting,	portland cement,	clinker, at plant/ CH/ kg
3,075E-05	10,676362	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter, u	pig iron, at plant/ GLO/ kg
1,567E-05	5,4398263	Operatior	Construction	Underground	Lining	transport, lorry >28t,	operation, lorry >28t	
1,501E-05	5,2100533	Operatior	Maintenance	Maintenance Lining	concrete,	portland cement,	clinker,	
1,196E-05	4,1535266	Operatior	Dismantle	Disposal Pressure Sh	disposal, reinforcement steel,	diesel, burned in building machine/ GLO/ MJ		
7,76E-06	2,6940185	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	pig iron, at plant/ GLO/ kg
6,911E-06	2,3991007	Operatior	Maintenance	Maintenance Suppor	concrete, exacting,	portland cement,	clinker, at plant/ CH/ kg	
5,588E-06	1,9400936	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	hot rolling,	natural gas, burned in industrial
3,54E-06	1,2288434	Operatior	Construction	Reversible Francis Tu	Pressure Shaft	chromium steel 18/8,	steel, converter	ferronickel, 25% Ni, at plant/ GLO/ I
3,459E-06	1,2006683	Operatior	Construction	Underground	Support Work Ch	transport, lorry >28t,	operation, lorry >28t,	
3,042E-06	1,056219	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	

STRUCTURAL PATH ANA Pumped Storage Facilities (construction-maintenance and end-of live)

fossil depletion/ GLO/ (H)

ABSOLUTE	RELATIVE	SEQUENCE:							
4,60182E-06	6,743541	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter, unalloye	pig iron	hard coal
2,58329E-06	3,785571	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter, unalloye	pig iron	hard coal
2,55336E-06	3,74172	Operation	Construction	Underground	Lining	concrete,	portland cement,	clinker,	hard coal
1,5208E-06	2,228598	Operation	Construction	Underground	Lining	concrete,	portland cement,	clinker,	heavy fuel oil, kg
1,48259E-06	2,172602	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter, unalloye	pig iron	hard coal
1,16916E-06	1,7133	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter, unalloye	pig iron	hard coal
1,11525E-06	1,634295	Operation	Construction	Underground	Lining	transport, lorry >28t,	operation, lorry >28t,	diesel, low-sulphur, at regional storag	
1,03033E-06	1,509855	Operation	Construction	Underground	Lining	concrete,	portland cement,	clinker,	heavy fuel oil

STRUCTURAL PATH ANALYSIS

human toxicity/ RER/ (H)

ABSOLUTI	RELATIVE	SEQUENCE:						
2,84E-05	28,42778	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, electric,	
3,55E-06	3,549824	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, converter, unalloyed,	pig iron,
2,38E-06	2,382904	Operatior	Construction	Reversible Francis Turbi	Pressure Shaft	chromium steel 18/8,	steel, converter, chromium	ferronickel, 25% Ni
2,32E-06	2,31802	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, converter, unalloyed,	pig iron,
2,12E-06	2,12213	Operatior	Construction	Reversible Francis Turbi	Pressure Shaft	chromium steel 18/8,	steel, electric,	
2,04E-06	2,043775	Operatior	Construction	Underground	Lining	concrete, exacting,	portland cement, strength c	clinker,
1,84E-06	1,839718	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, converter, unalloyed,	pig iron,
1,8E-06	1,801404	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, converter, unalloyed,	pig iron,
1,47E-06	1,469624	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, electric,	disposal, slag, electi
1,44E-06	1,438127	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, electric,	disposal, dust, EAF
1,4E-06	1,399483	Operatior	Construction	Reversible Francis Turbi	Pressure Shaft	chromium steel 18/8,	steel, electric, chromium	ferronickel, 25% Ni
5,98E-07	0,59852	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, converter, unalloyed,	ferronickel, 25% Ni
4,06E-07	0,405702	Operatior	Construction	Underground	Support Work Ch	reinforcing steel	steel, converter, unalloyed	

STRUCTURAL PATH ANALYSIS

natural land transformation/ RER/ (H)

ABSOLUTE	RELATIVE	SEQUENCE:						
7,72E-09	16,00145	Operatior	Construction	Underground	Lining	concrete, exacting,	gravel, round, at mine/ CH/ kg	
-4,7E-09	-9,69231	Operatior	Construction	Underground	Lining	concrete, exacting,	gravel, round, at mi	limestone mine/
3,8E-09	7,878342	Operatior	Dismantle	Disposal Pressure Sh	disposal, building,	diesel, burned in buildi	diesel, at regional s	diesel,
3,08E-09	6,377779	Operatior	Construction	Underground	Lining	transport, lorry >28t, fle	operation, lorry >28	diesel, low-sulpl
1,51E-09	3,122251	Operatior	Construction	Underground	Support Work Ch	reinforcing steel, at pla	steel, converter, ur	pig iron, at plant
1,39E-09	2,880262	Operatior	Maintenance	Maintenance Lining	concrete,	gravel, round,		
1,23E-09	2,548378	Operatior	Construction	Underground	Support Work Ch	transport, barge/ RER/ t	maintenance, operation, canal/ RER/	
-8,4E-10	-1,74462	Operatior	Maintenance	Maintenance Lining	concrete,	gravel, round,	recultivation, limestone mine/ CH/ r	

STRUCTURAL PATH ANALYSIS

urban land occupation/ RER/ (H)

ABSOLUTE	***RELATIVE***	***SEQUENCE:***								
1,59E-07	7,036007	Operation	Construction	Underground	Lining	concrete, exacting,	gravel, round, at mine			
1,56E-07	6,894067	Operation	Construction	Underground	Lining	transport, lorry >28	operation, maintenance, road			
1,17E-07	5,187725	Operation	Construction	Underground	Support Work Ch	transport, barge	maintenance, operation, canal			
7,96E-08	3,527776	Operation	Construction	Underground	Lining	concrete, exacting,	gravel, ro	mine, gravel		
5,51E-08	2,440945	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, con	pig iron, at p	hard coal	hard coa
5,06E-08	2,242222	Operation	Construction	Underground	Lining	concrete, exacting,	concrete mixing plantt			
4,9E-08	2,168997	Operation	Construction	Underground	Support Work Ch	reinforcing steel,	steel, ele	iron scrap,	scrap preparation	

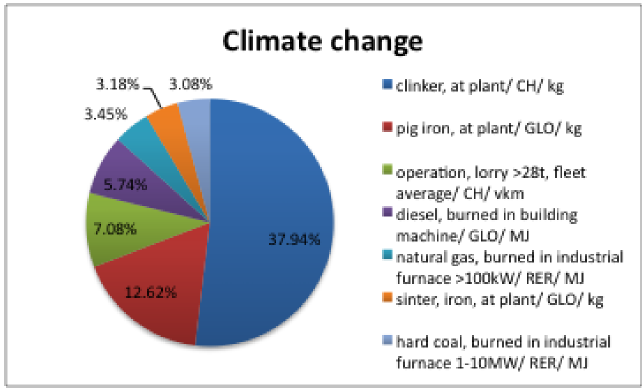
STRUCTURAL PATH ANALYSIS

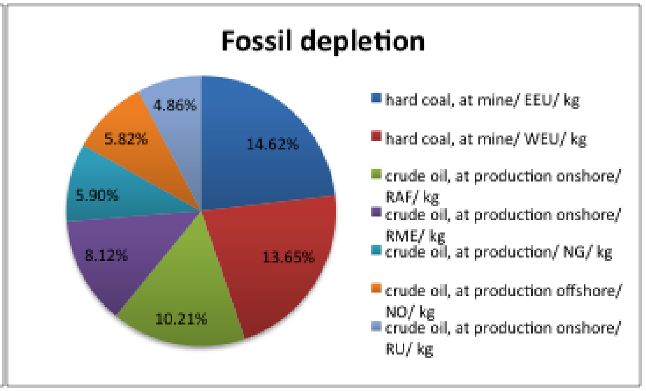
terrestrial acidification/ RER/ (H)

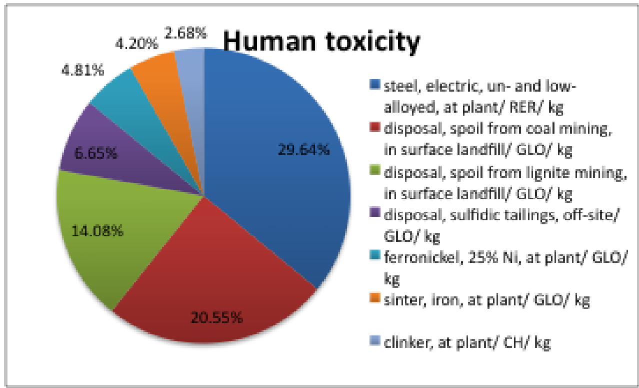
ABSOLUT	***RELATIVE***	***SEQUENCE:***							
1,47E-07	13,54415	Operatior	Construction	Underground	Excavation	blasting/ RER/ kg			
1,01E-07	9,289878	Operatior	Construction	Underground	Lining	concrete, exacting	portland cement	clinker, at plant	
9,74E-08	8,962796	Operatior	Dismantle	Disposal Pressure Sh	disposal, building,	diesel, burned in building machine			
8,68E-08	7,991089	Operatior	Construction	Underground	Lining	transport, lorry >28t, f	operation, lorry >28t		
5,92E-08	5,449134	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter	pig iron, at plant	sinter, iron,
2,35E-08	2,166718	Operatior	Construction	Reversible Francis Tu	Pressure Shaft	chromium steel 18/8,	steel, converter, chr	ferronickel, 25% N	hard coal, industria
2,14E-08	1,971456	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	pig iron, at plan	sinter, iron,
1,92E-08	1,763778	Operatior	Construction	Underground	Support Work Ch	transport, lorry >28t, f	operation, lorry >28t		
1,82E-08	1,672178	Operatior	Maintenance	Maintenance Lining	concrete, exacting	portland cement,	clinker,		
1,49E-08	1,37524	Operatior	Construction	Underground	Support Work Ch	reinforcing steel,	steel, converter,	pig iron, at plan	hard coal coke
1,38E-08	1,272517	Operatior	Construction	Reversible Francis Tu	Pressure Shaft	chromium steel 18/8,	steel, electric, chr	ferronickel, 25% Ni	hard coal,
1,36E-08	1,255084	Operatior	Construction	Underground	Support Work Ch	transport, barge	operation, barge		

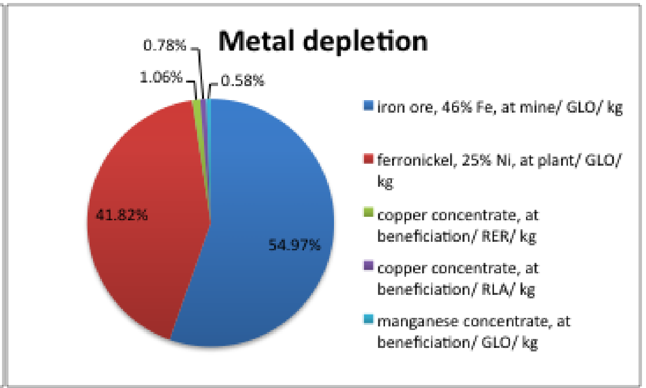
IX. Appendix I

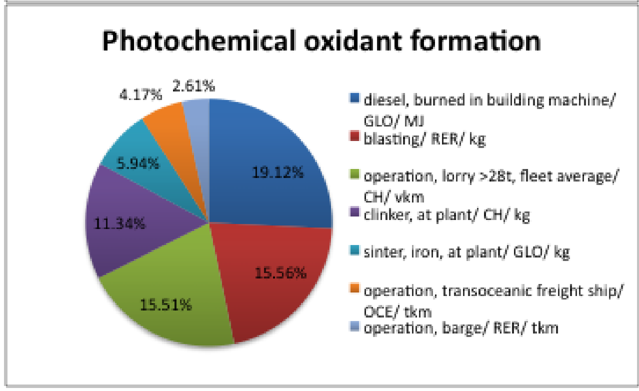
Detail Contribution analysis of the life cycle of the pumped storage plant excluding the operational phases, with the objective disclosure which are main resources and processes during the life cycle that contributes to each of the environmental impact categories evaluated.

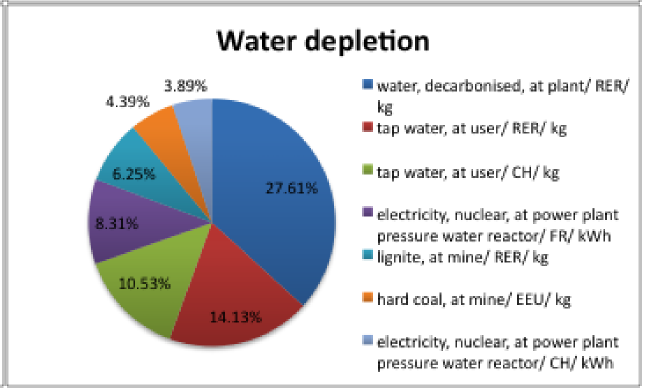


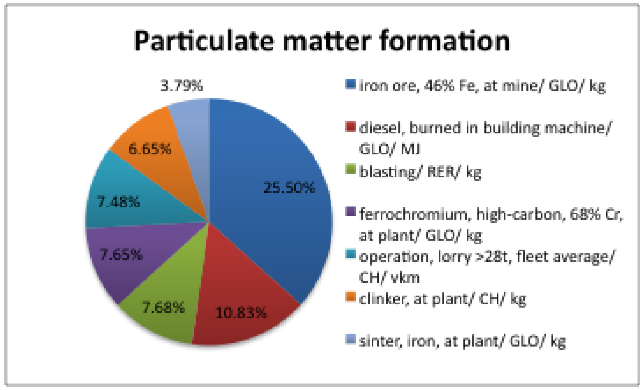


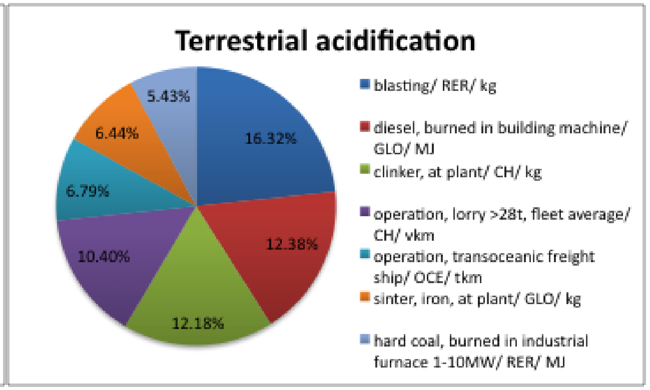

Human toxicity
29.64%
20.55%
14.08%
6.65%
4.81%
4.20%
2.68%
steel, electric, un- and low-alloyed, at plant/ RER/ kg
disposal, spoil from coal mining, in surface landfill/ GLO/ kg
disposal, spoil from lignite mining, in surface landfill/ GLO/ kg
disposal, sulfidic tailings, off-site/ GLO/ kg
ferronickel, 25% Ni, at plant/ GLO/ kg
sinter, iron, at plant/ GLO/ kg
clinker, at plant/ CH/ kg

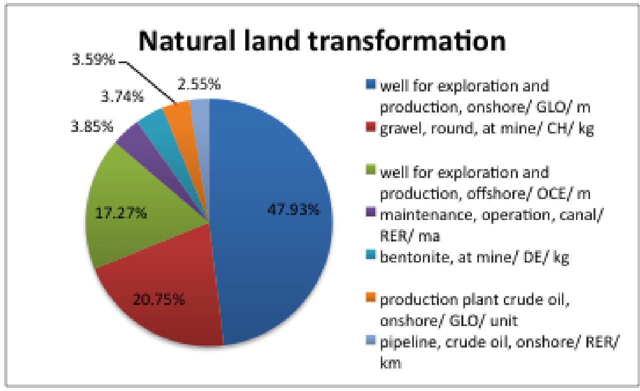

Metal depletion
54.97%
41.82%
1.06%
0.78%
0.58%
iron ore, 46% Fe, at mine/ GLO/ kg
ferronickel, 25% Ni, at plant/ GLO/ kg
copper concentrate, at beneficiation/ RER/ kg
copper concentrate, at beneficiation/ RLA/ kg
manganese concentrate, at beneficiation/ GLO/ kg

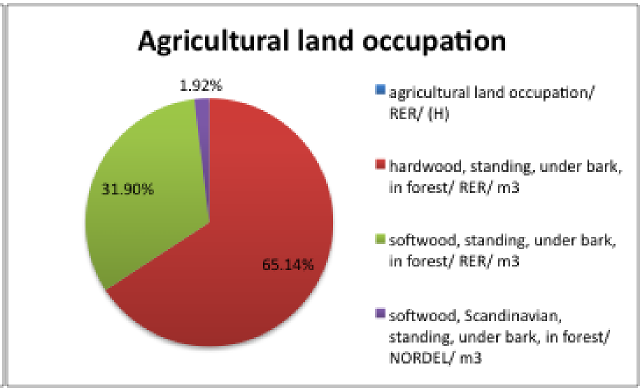

Photochemical oxidant formation
19.12%
15.56%
15.51%
11.34%
5.94%
4.17%
2.61%
diesel, burned in building machine/ GLO/ MJ
blasting/ RER/ kg
operation, lorry >28t, fleet average/ CH/ vkm
clinker, at plant/ CH/ kg
sinter, iron, at plant/ GLO/ kg
operation, transoceanic freight ship/ OCE/ tkm
operation, barge/ RER/ tkm

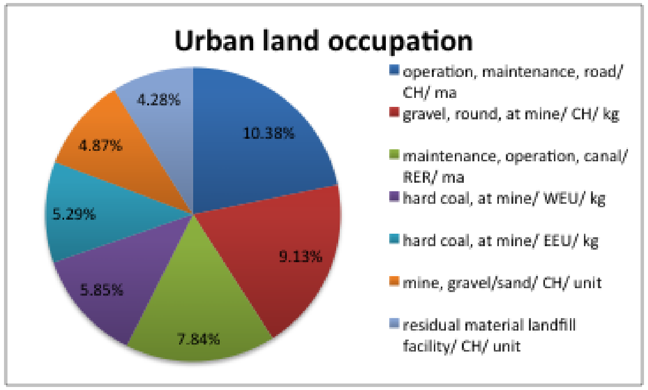

Water depletion
27.61%
14.13%
10.53%
8.31%
6.25%
4.39%
3.89%
water, decarbonised, at plant/ RER/ kg
tap water, at user/ RER/ kg
tap water, at user/ CH/ kg
electricity, nuclear, at power plant pressure water reactor/ FR/ kWh
lignite, at mine/ RER/ kg
hard coal, at mine/ EEU/ kg
electricity, nuclear, at power plant pressure water reactor/ CH/ kWh


Particulate matter formation
3.79%
6.65%
7.48%
7.65%
7.68%
10.83%
25.50%
iron ore, 46% Fe, at mine/ GLO/ kg
diesel, burned in building machine/ GLO/ MJ
blasting/ RER/ kg
ferrochromium, high-carbon, 68% Cr, at plant/ GLO/ kg
operation, lorry >28t, fleet average/ CH/ vkm
clinker, at plant/ CH/ kg
sinter, iron, at plant/ GLO/ kg


Terrestrial acidification
5.43%
6.44%
6.79%
10.40%
12.18%
12.38%
16.32%
blasting/ RER/ kg
diesel, burned in building machine/ GLO/ MJ
clinker, at plant/ CH/ kg
operation, lorry >28t, fleet average/ CH/ vkm
operation, transoceanic freight ship/ OCE/ tkm
sinter, iron, at plant/ GLO/ kg
hard coal, burned in industrial furnace 1-10MW/ RER/ MJ


Natural land transformation
3.59%
3.74%
2.55%
3.85%
17.27%
20.75%
47.93%
well for exploration and production, onshore/ GLO/ m
gravel, round, at mine/ CH/ kg
well for exploration and production, offshore/ OCE/ m
maintenance, operation, canal/ RER/ ma
bentonite, at mine/ DE/ kg
production plant crude oil, onshore/ GLO/ unit
pipeline, crude oil, onshore/ RER/ km


Agricultural land occupation
1.92%
31.90%
65.14%
agricultural land occupation/ RER/ (H)
hardwood, standing, under bark, in forest/ RER/ m3
softwood, standing, under bark, in forest/ RER/ m3
softwood, Scandinavian, standing, under bark, in forest/ NORDEL/ m3


Urban land occupation
operation, maintenance, road/ CH/ ma
gravel, round, at mine/ CH/ kg
maintenance, operation, canal/ RER/ ma
hard coal, at mine/ WEU/ kg
hard coal, at mine/ EEU/ kg
mine, gravel/sand/ CH/ unit
residual material landfill facility/ CH/ unit
10.38%
9.13%
7.84%
5.85%
5.29%
4.87%
4.28%