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Harvesting factor in hydropower generation

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ABSTRACT: Discussions on the future energy supply lead to a comprehensive consideration of energy production and energy efficiency. Therefor an investigation of the whole lifecycle is needed to give an impression of the environmental performance. The aim of this paper is to show the environmental impacts of a hydropower plant over its lifecycle in a holistic approach. Accordingly, a life cycle assessment based on the bill of quantities of a small hydropower project was carried out to calculate its environmental impacts. Furthermore, the full ecological potential in terms of saved greenhouse gas emissions was indicated. Finally, the cumulated energy demand from the plant was then put in relationship to the produced energy of the hydropower plant, to create a so-called harvesting factor. The environmental impact clearly shows that the use of hydropower is more sustainable than other energy production technologies due to its low impacts on global warming potential.

1 INTRODUCTION

The European union attempts to concentrate on promoting renewable energy sources (Directive 2009/28/EC, 2009). To guarantee the future energy supply and focus on more import dependency of energy, many European countries have adopted this in their national programs to achieve the guidelines of the European energy policies. In Austria this is carried out using the Austrian strategy, which is strongly focused on hydropower (BMWFJ, 2010). Due to its topographical situation, Austria has significant hydropower resources. A survey by Pöyry Energy estimated that an available hydropower potential about 7 TWh would be realized by 2020 (Pöyry, 2008).

Most hydropower resources are already developed, but there are still capacities left. One of the main potentials are small hydropower plants that contain hydropower with a maximum capacity of less than 10 MW. That means – especially in Styria – that there remains a big potential between 1.5 – 2.5 TWh that could be realized in the next few years.

For the further developments of power generation, it is necessary to know the energy efficiency of the different technologies to make decisions on how a sustainable future energy mix could be provided. Hydropower generation in particular has to deal with the restrictions of the European water framework directive (Directive 2000/60/EC, 2000) and the new requirements due to the liberalization of the European electricity market (Wall, 2010). However, the increasing demand for electricity has to be satisfied as well, and resources are limited and uncontrolled rising demand is not sustainable. Thus energy efficiency has to be considered. In the last years, classification regarding environmental performance has become more and more popular especially due to European activities, i.e. the work of CEN/TC350 (CEN, 2010), (CEN, 2011), (Passer, 2010).

However, the carbon footprint (IPCC, 2007) is one of the major measurements on which the media has focused, with industry striving to attain carbon neutrality in both operation and products. Also, according to the upcoming third emissions trading period (Directive 2003/87/EC, 2003), how emissions are calculated in the future and how they are determined during the operation of the hydropower plant is a point of interest.

Using the method of life cycle assessment (LCA), the environmental performance of different power generation technologies can be evaluated. A similar investigation has been performed on a Swiss hydropower plant published as an environmental product declaration (EPD) (AXPO, 2007).

2 METHOD

In terms of a comprehensive investigation of hydropower generation, a life cycle assessment was performed to investigate the whole energy flows and calculate the cumulative energy demand. To determine the entire environmental burden, it is furthermore necessary to consider the material-related in- and output flows of the chosen hydropower plant to build, operate and decommission it.

A method to determine the energy payback ratio is provided by the harvesting factor, where the energy output has to be put into a relation to the cumulative energy demand (see Figure 8).

2.1 *Life cycle assessment*

For the life cycle assessment (LCA), the approach of the ÖNORM EN ISO 14040 (ISO, 2006a) and ÖNORM EN ISO 14044 (ISO, 2006b) was chosen, as shown in Figure 1.

The concept of a LCA can be distinguished as a four-step procedure starting with the goal and scope definition, setting up the inventory (inventory analysis) of relevant inputs and outputs from the system and calculating the potential environmental impacts (impact assessment) and doing an interpretation with respect to the aim of the study.

For the study, a reference period of 100 years has been taken, according to the period related to the water law permission (WRG, 1959) for running a hydropower plant on a river in Austria.

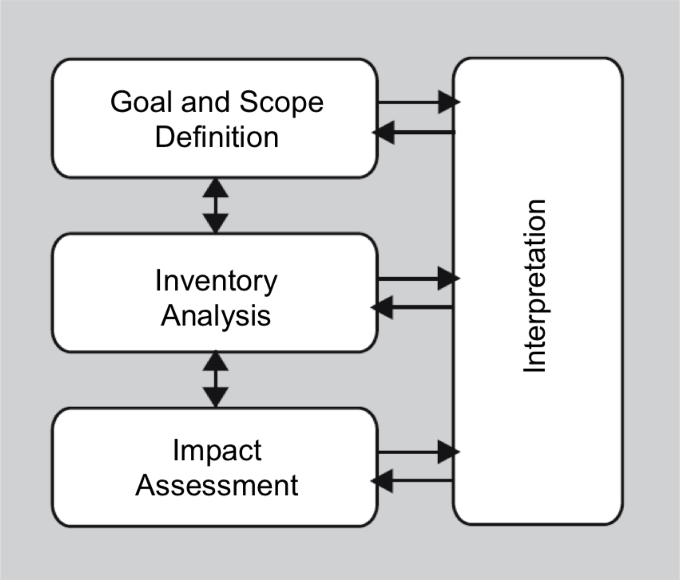


Figure 1. Life Cycle Assessment Framework according to EN ISO 14040.

2.2 *Life Cycle Inventory Analysis*

The assessment is based on the bill of quantities at the stage of the tender procedure regarding a small hydropower plant.

For the LCI, the entire life cycle stages were taken into account. As a framework, the FprEN 15804 was chosen to perform the investigation. This means everything is taken into account starting from the construction with the used products (product stage and construction process stage) up to the maintenance works (use stage). This also takes into account the decommissioning of the power plant at the end of its life time (end of life stage), as shown in Figure 2.

The whole project was considered in terms of the site development and the connection to the local electricity grid for transporting the produced electricity to the costumers.

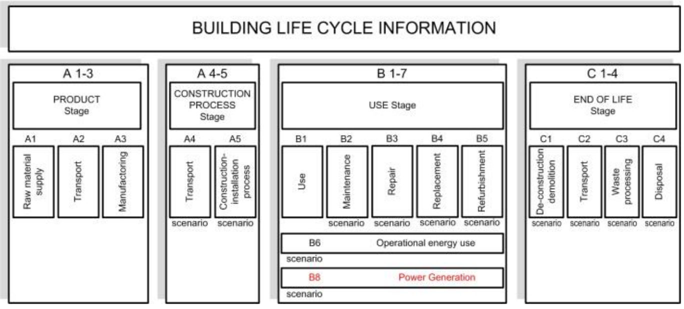


Figure 2. Stages of the building assessment according to the CEN/TC350 FprEN 15804 standard.

2.3 *Life Cycle Impact Assessment*

To calculate the environmental impacts caused by the hydropower plant during its life cycle, several indicators have been chosen according to the FprEN 15804 (see Table 1).

Table 1. Impact categories according to FprEN 15804

Impact category	Unit
Acidification AP	[kg SO2-Eq]
Eutrophication EP	[kg PO4-Eq]
Global warming potential GWP	[kg CO2-Eq]
Stratospheric ozone depletion ODP	[kg CFC-11-Eq]
Photooxidant pollution POCP	[kg ethylene-Eq]
Cumulative energy demand renewable CED r	[MJ-Eq]
Cumulative energy demand non-renewable CED nr	[MJ-Eq]

Subsequently the Ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories, 2004) was used to calculate the environmental impacts and the cumulative energy demand. This database contains more than 4000 life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals and transport services.

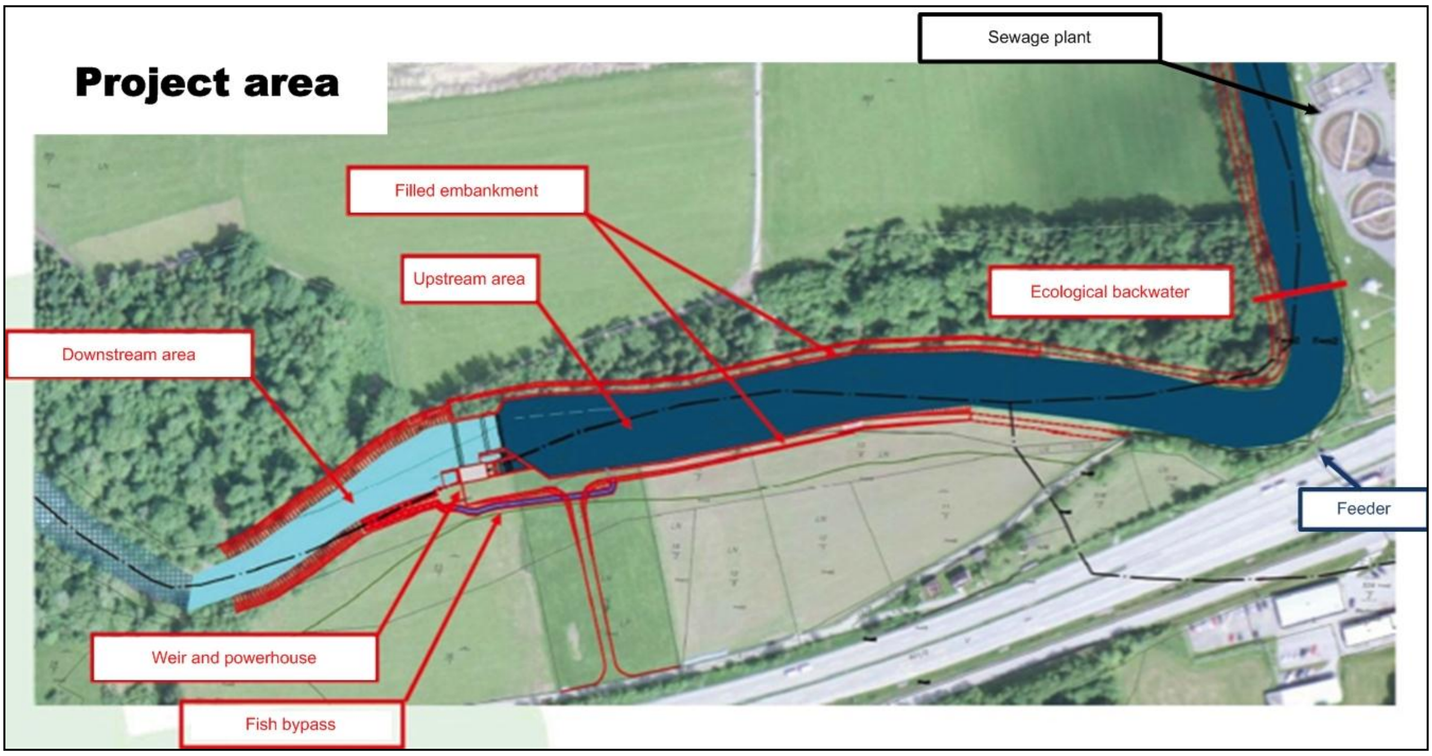


Figure 3. Overview of the hydropower project.

In presenting the results, all impact categories have been selected to show a complete picture. To determine the harvesting factor, it is necessary to focus on the cumulative energy demand. Referring to the third emissions trading period (European Parliament and Council, 2003), the selected categories, especially including the global warming potential (GWP) throughout the entire life cycle of the hydropower plant, have also been investigated in detail.

2.4 *Hydropower project*

The case study is a small hydropower plant, located on a small river in Northern Styria, Austria (Wall, 2011). The project is owned and operated by Energie Steiermark AG, 2011. Figure 3 shows the site map of the downstream area, the powerhouse, the weir and the access road. The reservoir in the upstream area requires filled embankment dams on each side to handle the storage. In the backwater area, special measures are necessary to handle the outlet of the sewage plant above.

Two main factors influence the amount of electricity a hydropower plant produces. The first parameter depends on the discharge and the second one on the falling height. In the cross section in figure 4, the hydraulic height is about 5.2 m. The discharge is about 17.5 m^3/s. This means the hydropower plant is designed for a capacity of 730 kW with a regular work capacity over 3600 MWh/a.

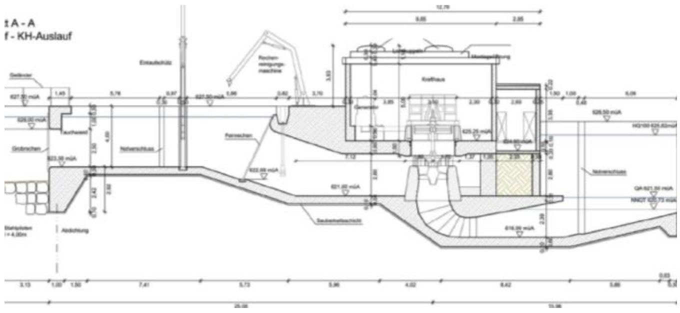


Figure 4. Cross section of the hydropower project.

To determine the material flows for the hydropower plant, the project was first split into the different construction stages:

- Exploration and diversion
- Construction of the weir and powerhouse
- Upstream area
- Downstream area
- Accompanying measures
- Access to the power grid
- Electro-mechanical equipment
- Hydraulic steel structures
- Maintenance measures

In the next step, these stages have been looked at in more detail by splitting them up into the specific construction works.

For the construction works, every step involving excavation work, transportation, earthwork modeling and slope stabilization was investigated. Also, the expenses for the reinforced concrete works and the production of concrete were taken into account.

For the functionality of the hydropower plant the electro-mechanical equipment was also considered.

Based on the project data, manufacturers were contacted for providing an inventory of used materials for the respective machinery, such as turbine, transformer, generator and hydraulic steel components. The provided information was divided up to show the specific material information and the production process.

2.5 *Works during the operation of the facility*

As for the current hydropower plant, 100 years is taken into account for the life cycle, and one replacement stage after fifty years has been assumed. This work includes the replacement of steel components for hydraulic parts as well as parts of the power generation equipment. This means that, in terms of the power generation equipment, the electromechanical equipment such as turbines, power transformers and generators and for the hydraulic steel parts, weir traps and gates are replaced. A detailed overview of the revision and maintenance works is listed in Table 2.

For the operation of the power station, 2 % of the produced energy is needed. Furthermore, the consumption of lubrication oil has to be taken into account, and this has been assumed to be 0.007 g of oil per produced kWh of the hydropower station.

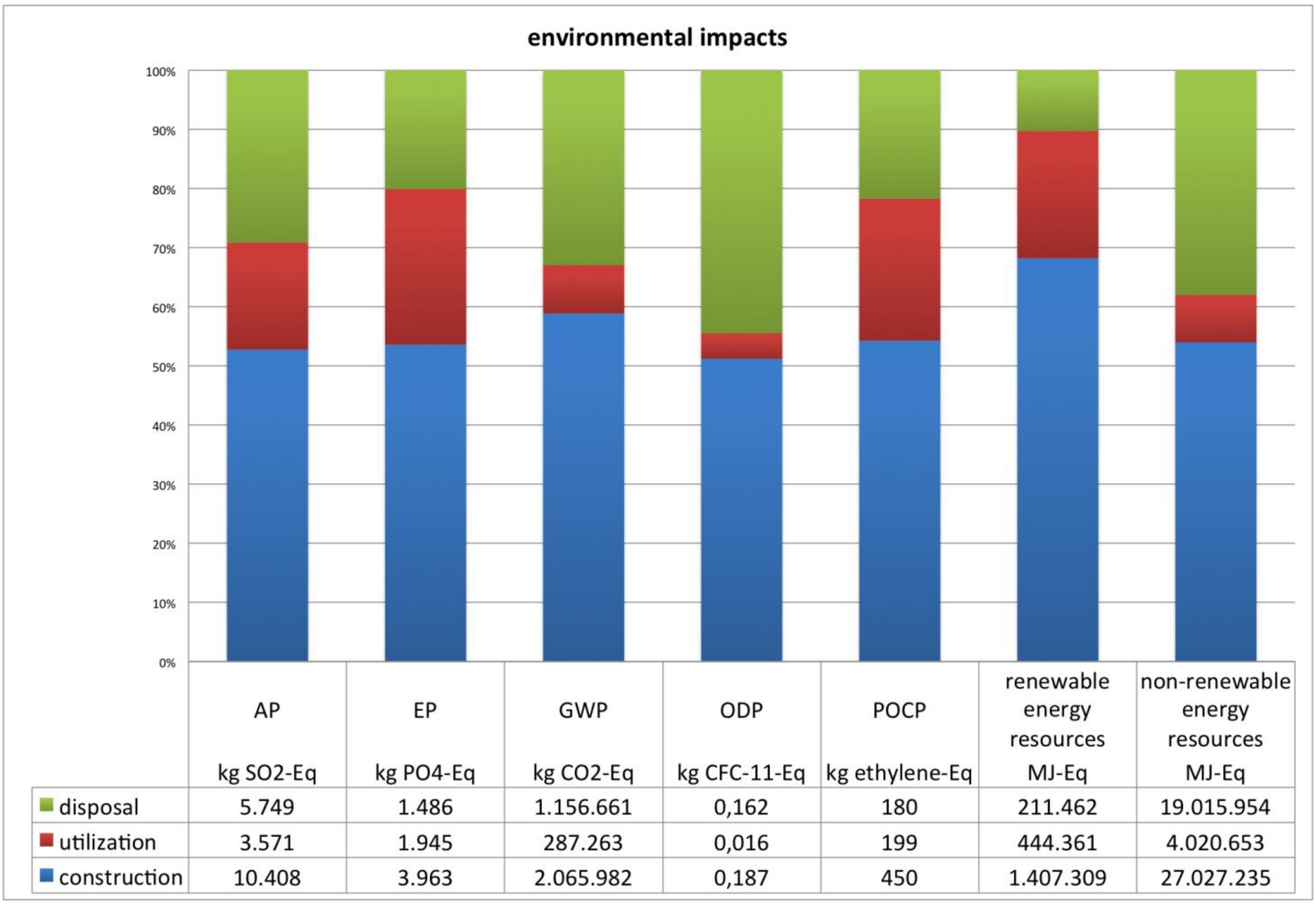
Table 2. Revision and maintenance works

Interval	Components
after 50 years	Replacement of electro-mechanical equipment Turbine Generator Transformer
	Replacement of hydraulic steel components gates and sluice gates rake screens inlet rakes hydraulic equipment

3 RESULTS

In line with the European EPD framework, an overview of the environmental impacts is given in the following chapter and the results are described, referring to:

- Environmental impacts
- Cumulative energy demand
- Global warming potential
- Harvesting factor
- Sensitivity analysis
- Comparison with other plants



	AP kg SO2-Eq	EP kg PO4-Eq	GWP kg CO2-Eq	ODP kg CFC-11-Eq	POCP kg ethylene-Eq	renewable energy resources MJ-Eq	non-renewable energy resources MJ-Eq
🟩 disposal	5.749	1.486	1.156.661	0,162	180	211.462	19.015.954
🟥 utilization	3.571	1.945	287.263	0,016	199	444.361	4.020.653
🟦 construction	10.408	3.963	2.065.982	0,187	450	1.407.309	27.027.235

Figure 5. Environmental impacts of the hydropower plant.

3.1 *Environmental impacts*

The results of the LCA for the hydropower plant for the chosen impact categories (AP, EP, GWP, OPD, POCP, CEDr and CEDnr) for the whole life cycle are shown in Figure 5. The contribution of the construction stage is in blue, the operation stage red and the impacts of disposal is green.

Generally, more than 50 % of the environmental impacts are incurred in the construction stage of the hydropower plant due to the high impact of the construction processes and the related construction products. But the interpretation for eutrophication (EP) and photooxidant potential (POCP) show quite a significant impact in the utilization period of the hydropower plant. These impacts result from the use of lubrication oil to operate the hydro-mechanical equipment.

3.2 *Cumulative energy demand*

For a more detailed knowledge of the distribution on the different impacts, a more comprehensive investigation has been performed. For this reason, the different construction stages with their environmental impacts have been worked out over the whole life cycle of the hydropower plant. The contribution to the cumulative energy demand – both renewable and non-renewable – are pictured in Figure 6, whereas the red bars indicate the cumulative energy demand of non-renewable sources and the blue ones the cumulative energy demand of renewable sources.

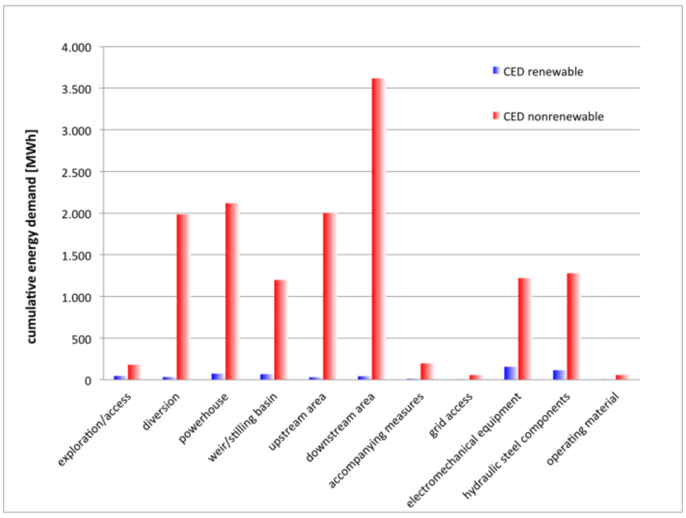


Figure 6. Cumulative energy demand of the construction stage.

From this detailed view it can be seen that the main impacts result from the construction phase, because the main work is carried out at this stage. That means the excavation and modeling of the downstream area shows the highest impact, with impacts related to earthworks and concrete works. The results are somehow surprising because a closer look at the origins of some expenses show clearly the big impacts of transportation. Second largest impacts in the ranking of the construction works are the upstream area and the diversion.

The electromechanical equipment and hydraulic steel components incur approx. 1250 MWh each to produce and transport.

Due to the production processes and the use of building components which result from non-renewable primary energy sources the percentage of renewable energy is really small with regard to the whole project. However, the largest share of renewable energy results from the manufacturing of these components taking into account the Austrian production conditions e.g. electricity production mix.

3.3 *Global warming potential*

The results for the environmental impact category GWP are pictured in Figure 7. At first sight, the results look quite similar to the ranking of the results of CEDnr although the greenhouse gas emissions are slightly higher from single construction works due to the impact of the construction machinery. This is caused by the fact that the construction machinery is powered by diesel-fueled engines, which cause such a high amount of impact.

The second largest contribution is caused by the powerhouse due to the production of cement for the concrete. This can be evaluated in detail by taking a look at the specific datasets for the concrete within the Ecoinvent datasets.

The third largest contribution to the environmental impact category GWP comes from the weir, the upstream area and the diversion.

Due to the large amount of excavation work at the downstream area and the construction of the dams in the upstream area, the impact of building machines and the transport of the excavation material is significant. Accordingly, scenarios were set up for the transportation processes and a more specific analysis was carried out. The results are presented in chapter 3.5 Sensitivity Analysis.

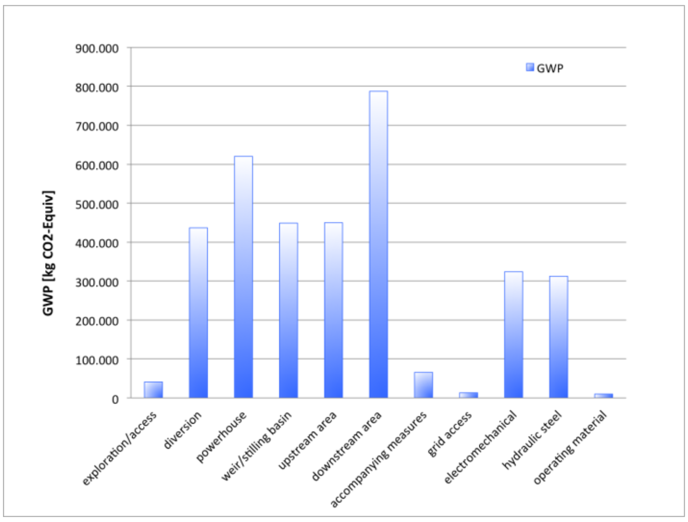


Figure 7. Global warming potential of the construction stage.

In Contrast to the other work, the electro-mechanical equipment and the hydraulic steel components do not show such high environmental impacts. A possible reason for this is that the LCIA is based on the Austrian production situation. In other words, the electricity demand for electric steel has been calculated with the Austrian electricity production mix. On the basis of the Austrian electricity dataset, an amount of approx. 62 % of hydropower in the electricity production mix results in a lower environmental impact compared to steel-datasets from other countries with different electricity generation mixes.

3.4 *Harvesting factor*

The harvesting factor, also known as the energy payback ratio, is the total energy produced during a system's lifespan divided by the energy required to build, operate, maintain and decommission the facilities. Figure 8 illustrates an overview of the single lifecycle stages with their contribution to the CED and the harvesting factor, respectively. The biggest amount of energy is consumed in the construction stage, and only a small energy demand is needed to run the power plant after commissioning. After 50 years, a major revision is needed to change the electro-mechanical equipment and the hydraulic steel components. The facility is dismantled and disposed of after the considered life cycle of 100 years. But in relation to construction, this impact does not influence the demand of energy so much.

A high ratio of the harvesting factor indicates a good energetic performance, which does not necessary correlate with the environmental performance. A harvesting factor greater than 1 means that the system generates more energy than it consumes. Referring to some literature data (Gagon, 2005) harvesting factors >1 are quoted for nuclear and fossil power generation. To understand these results the calculated lifecycle has to be considered as well as the system boundaries.

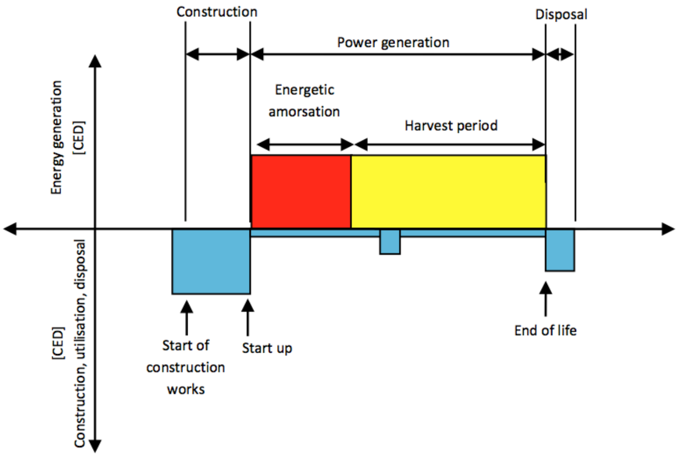


Figure 8. Illustration of determining the harvesting factor.

A harvesting factor of 25 was calculated for the selected case study. This means that taking into account the whole life cycle of the hydropower plant, the cumulative energy demand is 25 times more than the demand for the construction, maintenance measures and decommission of the power plant.

3.5 *Sensitivity Analysis*

The results of the LCIA show high environmental impacts from the construction machinery, especially transport related to excavation work. Regarding the sensitivity analysis, several transportation scenarios have been developed to evaluate their impacts and to show the major impacts of the distances on the harvesting factor (Table 3).

Table 3. Impact of different transportation scenarios on the harvesting factor.

Typ of transport	**Distances**	**TR 1**	**TR 2**	**TR 3**
Earthworks	km	20	50	100
Concrete transportation	km	20	40	80
Hydraulic steel structures, electro-mechanical equipment and other transports	km	50	100	500
Harvesting factor		**37**	**25**	**16**

The scenarios are based on different processes regarding the construction management. TR1 is the scenario with the least transport distances, TR2 average and TR3 the one with the highest. The assumed transportion distances consider both directions (to and from site).

Transportation scenario 1 (TR1) refers to short distances – especially earthworks. Distances are short due to the close vicinity of landfill areas and other places where surplus excavation material is dumped. The transportation distances for concrete are limited due to the solidification processes of concrete (approx. 90 minutes), which have to be considered in every scenario. But the transportation of steel and earth are just limited by economic reasons.

TR2 represents the average transportation scenario according to similar projects realized by Energie Steiermark AG, which has been considered for the main determination of the environmental impacts.

The scenario TR3 shows the effects of economically driven construction management without considering the ecological impacts and carbon footprints of the construction products. This situation influences the harvesting factor significantly and leads to a low energy payback ratio from the environmental point of view.

The results of the sensitivity analysis lead to the conclusion that further investigations of chosen transportation scenarios and related processes should be undertaken due to the fact that different transportation distances influence the harvesting factor significantly.

3.6 *Comparison of the results*

As a last step, these results were compared with other published data for small hydropower plants. It was noticed that they are in the line with data from Kaltschmitt and Hydro Quebec. Additionally the results are compared with the datasets from the Ecoinvent-database as following:

- Small hydropower plant project
- Electricity hydropower AT (Ecoinvent, 2004a)
- Electricity hydropower CH (Ecoinvent, 2004b)
- Electricity production mix AT (Ecoinvent, 2004c)
- Electricity production mix DE (Ecoinvent, 2004d)
- Electricity production mix RER (Ecoinvent, 2004e)
- Electricity production mix UCTE (Ecoinvent, 2004f)

First, the environmental impacts of the indicator GWP for the different electricity production mixes are illustrated in Figure 9. The reason for the better performance of the European mix (RER) in comparison with the UCTE mix is that the Norwegian production mix contains hydropower up to almost 100 %.

The results of the LCIA determine a global warming potential of about 9.78 g/kWh. This means that there is a saving on greenhouse gases of about 300 g/kWh compared to the average Austrian energy production (Mix AT) using the Ecoinvent dataset of the average Austrian electricity production.

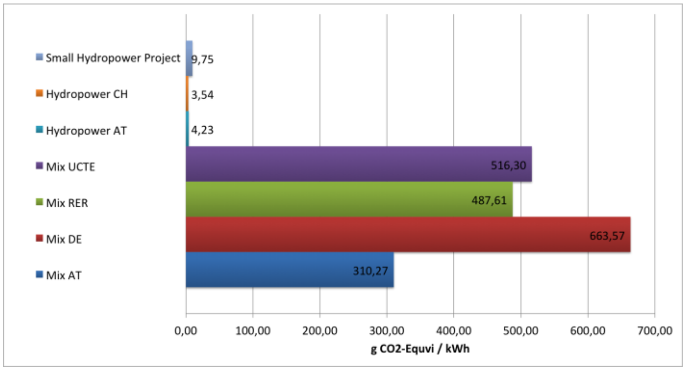


Figure 9. Comparison of GWP of different electricity production mixes in Europe.

A crosscheck using existing data from the Ecoinvent database shows clearly that the result of 9.78 g/kWh GWP is consonant to the average global warming potential of Austria 4.2 g/kWh and Switzerland 3.5 g/kWh for hydropower electricity generation. The reason why the calculated GWP is nearly twice these values is because of the size and installed power of the plants.

Furthermore, the results indicate clearly how sustainable the electric energy supply from hydropower is in comparison with other energy forms (Figure 10).

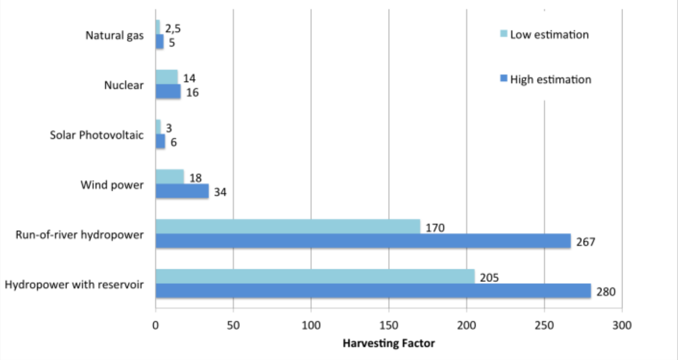


Figure 10. Harvesting factor of different electricity generation options (illustration acc. to Hydro Quebéc).

The calculated harvesting factor is in the line with published harvesting factors determined for similar small hydropower plants as reported by Kaltschmitt and Streicher, 2009, which ranges from 17-39, respectively.

Corresponding to the investigations of the energy payback ratio performed by Hydro Quebec (Gagon, 2005), higher ratios for large-scale hydropower plants are shown. Additionally, the performance of hydropower plants with reservoirs is even better and values can achieve up to 205. The reason for such a good performance is due to the fact that the construction work does not have such a high impact as the amount of energy that can be generated by using vertical height differences as well as the larger amount of water to produce electricity. The reason for this is that for power generation, it is the height and the discharge that basically matters.

4 CONCLUSIONS

This work demonstrates that a LCA, based on the framework of the ISO 14040 and FprEn 15804, can be applied to hydropower plants. The environmental impacts can be calculated using these standards.

The results of the study show that the related electricity generation of the small hydropower plant is clearly sustainable. The harvesting factor of 25 (energy payback ratio) is significantly positive. This means that the power plant provides more energy over its life cycle compared to the amount of energy needed to build, operate maintain and decommission the power plant. For further comparison with other power generation technologies, it is recommended to look at the whole environmental impacts. Just focusing on the harvesting factor would not be satisfactory.

In further research projects taking into account the life cycle performance, the LCA method can be used to give an overview of the energy efficiency of different energy generation methods.

Additionally, it would be interesting to combine these results with economic effects in order to show how the environmental improvement has an influence on the economic performance of a hydropower plant. Life cycle cost analysis (LCCA) can help to show how environmental improvements (e.g. different construction techniques or construction material use) are advantageous and also pay off in the economic performance of a hydropower plant.

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