Life Cycle Inventories of Hydroelectric Power Generation

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commissioned by
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Zusammenfassung

In der vorliegenden Studie werden die Ökobilanzen der Stromerzeugung mit Was¬serkraft dokumentiert. Es handelt sich hierbei um eine umfassende Aktualisierung und Erweiterung der Sachbilanzdaten des ecoinvent Datenbestandes v2.2, welche auf den Mitte der neunziger Jahre an der ETH Zürich erarbeiteten Ökobilanzdaten (Ökoinventare von Energiesystemen) basieren.

Neben Speicher- und Flusskraftwerken wurden neu auch Kleinwasserkraftwerke bilanziert, wobei unterschieden wird zwischen Kraftwerken, die in Anlagen der Wasserversorgung (Bewässerung, Trinkwasserbereitstellung) eingebunden sind, und alleinstehenden Kraftwerken. Die Grösse der bilanzierten Kraftwerke entspricht dem produktionsgewichteten Durchschnitt aller Speicher- beziehungsweise Laufwasser- oder Kleinwasserkraftwerke der Schweiz.

Daten zum Materialbedarf von Wasserkraftanlagen wurden revidiert und zum Teil mit Informationen aus neuen Publikationen ergänzt. Beton, Kies und Zement sind die massenmässig wichtigsten Baustoffe, wobei bei den bilanzierten Kraftwerken oftmals entweder die Menge Beton, oder die Mengen Zement und Kies bekannt sind. Im Weiteren werden Stahl in unterschiedlichen Qualitäten, Kupfer (neu in die Bilanzen aufgenommen) und weitere, hier nicht aufgeführte Baustoffe und Materialien eingesetzt.

Gemäss aktuellen Forschungserkenntnissen liegen die direkten Treibhausgas-Emissionen pro kWh Strom aus alpinen europäischen Speicherseen bei rund 1.4 g CO_2-eq/kWh, bei Speicherkraftwerken in gemässigten Zonen gehen wir von rund 12 g CO_2-eq/kWh aus. Bei den Laufwasserkraftwerken spielt es eine Rolle, ob diese einen Stausee aufweisen oder nicht. Bei Laufwasserkraftwerken mit Stausee liegen die Methan-Emissionen bei 0.67 g pro kWh (knapp 13.4 g CO_2-eq/kWh).

Ein weiterer wichtiger Aspekt stellt die Modellierung des Strombedarfs der Speicherpumpen dar. Hierbei handelt es sich um diejenigen Pumpen, welche einem Stausee Wasser aus einem anderen Einzugsgebiet oder aus tieferen Lagen zuführen.[1] Neu wird dieser Netzstrombedarf als Aufwand verbucht und nicht beim produzierten Wasserkraftstrom in Abzug gebracht.

Die Treibhausgas-Emissionen der Bereitstellung von Strom mit Wasserkraftwerken sind vergleichsweise tief und schwanken zwischen 2 g CO_2-eq/kWh ab Klemme integrierter Kleinwasserkraftwerke, 3.8 g CO_2-eq/kWh ab Klemme Laufwasserkraftwerk, 5.9 g CO_2-eq/kWh ab Klemme alpinem Speicherkraftwerk (netto, ohne Zulieferpumpen), und rund 16.6 g CO_2-eq/kWh ab Klemme Speicherkraftwerk in gemässigten Zonen.

Werden die hier bereitgestellten Sachbilanzdaten zu Flusswasserkraftwerken auf Anlagen grösserer Leistung angewendet, dürften die Aufwendungen und damit auch die kumulierten Emissionen tendenziell überschätzt werden. Dies entspricht einer konservativen Vorgehensweise.

Die in diesem Bericht beschriebenen Sachbilanzdaten sind in Übereinstimmung mit den Qualitätsrichtlinien des ecoinvent Datenbestands v2.2 erhoben und modelliert und werden im Datenformat EcoSpold 1 zur Verfügung gestellt.

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[1] Speicherpumpen sind nicht zu verwechseln mit den Pumpspeicherpumpen, welche dazu dienen, zu Niedertarifzeiten Wasser aus einem tiefer liegenden Becken in ein höher gelegenes zu pumpen, um es zu einem späteren Zeitpunkt (Hochtarif) wieder zu turbinieren.

Summary

The aim of this study is to describe the environmental impacts of construction, operation and deconstruction of hydroelectric power stations. The main focus is on power plants and their conditions in Switzerland. The LC inventories are then extrapolated to alpine and non-alpine regions of Europe and, in the case of storage power stations, to Brazil. Storage and pumped storage power stations, run-of-river power stations with and without reservoirs and their mix as well as small hydropower stations are covered in this report. Small hydropower stations are differentiated between stations that are integrated in existing waterworks infrastructures and standalone small hydropower stations. The inventory is composed of the three life cycle phases construction, operation and deconstruction. The following inputs are examined: consumption of cement, explosive agents, steel, copper, gravel, energy consumption of the construction, transport services (road and rail), land use, useful capacity of the reservoirs, turbined water, particle emissions during construction, oil spill to water and soil and the emissions of greenhouse gases from construction machines as well as from reservoirs (CO_2, CH_4, N_2O) and from electrical devices (SF_6) emitted during the operation. All life cycle inventory datasets established in this study are in compliance with the quality guidelines of ecoinvent data v2.2. They are provided in the EcoSpold v1 data format.

Content

1 Introduction

1.1 Scope of the study

Hydropower is widely perceived as a clean energy source as it is renewable and, until recently, it is assumed that the operation of hydropower stations causes hardly any emissions of pollutants. In this study the environmental impacts of electricity from hydroelectric power stations in each stage of their life cycle (construction, operation, dismantling) are quantified.

The first environmental impacts occur during the construction of the power stations. This includes the activities of the construction itself and the production and transport of the materials used (e.g. cement). Furthermore, there are hydrological aspects. The construction and operation of hydropower stations influences the spatial and temporal patterns of the water flow.

The aim is to describe the most important aspects of the environmental impacts of hydropower stations in Switzerland. The following parameters are considered: consumption of cement, explosive agents, steel, copper, gravel, energy consumption of the construction, transport services (road and rail), land use, useful capacity of the reservoirs, turbined water, particle emissions during construction, oil spill to water and soil and the emissions of greenhouse gases from construction machines as well as from reservoirs (CO_2, CH_4, N_2O) and from electrical devices (SF_6) emitted during the operation.

Storage and pumped storage hydropower stations, run-of-river hydropower stations and small hydropower stations are analysed. It is not the intention to characterise single hydropower stations but to find average data representing the hydropower mix in Switzerland and other European and non-European countries.

The main part of the study is the identification and quantification of the material and energy demand and the emissions caused and the waste produced. The total material and energy demand is applied to the net electricity production. It is difficult and, if at all possible, very sumptuous to access original data. Most of the Swiss hydropower stations have been constructed decades ago. The enormous labour was divided between different contractors which had sub-contractors themselves. Therefore it is nearly impossible to access all the information needed, if it is stored at all. The data used in this study are based on earlier studies (Bolliger & Bauer 2007; Frischknecht et al. 1996) and their sources. Additional information is gained from new publications such as from Vattenfall (2008) and Axpo (2008). The data sets on small hydropower stations are based on the students thesis of Jean-Baptiste and Konersmann (2000) and on Baumgartner and Doka (1998). Statistical data on the electricity production and the installed capacity are gained from up to date statistical publications of the BFE (2010a, b, 2011b).

1.2 State of the hydropower production

1.2.1 Switzerland

Hydropower is the most important renewable energy source in Switzerland. In 2010 37.5 TWh of hydroelectricity were produced, which is 56.5 % of the total electricity generation in Switzerland in 2010. 24.2 % is generated from run-of-river hydropower stations, 32.3 % from storage hydropower stations. In the electricity statistics of the Swiss Federal Office of Energy, the pumped storage hydropower stations (i.e. basic water flow plants) are not registered as electricity production sites because they show a net electricity consumption. (BFE 2011a).

According to the hydropower statistics of 2010 (BFE 2011c) the Swiss hydropower stations have an expected electricity production volume of 35.6 TWh. As shown in Tab. 1.1, over half of it is generated in storage hydropower stations and the run-of-river hydropower stations contribute 47 %. The total installed capacity is 13.3 GW (BFE 2011a, c). In 2008, small hydropower stations (<300 kW) had a production volume of 3’400 GWh, which is around 10 % of the total annual hydropower electricity production. The capacity of small hydropower stations is 760 MW[2].

Tab. 1.1: Expected production volumes of the hydropower stations in Switzerland, including hydropower stations with an installed capacity of >300 kW. Pumped storage hydropower plants are not included in total (BFE 2011c).

Power station	**Production volume (GWh)**	**Percentage**	**Capacity (MW)**	**Percentage**
Run-of-river hydropower stations	16’611	46.7 %	3’707	27.5 %
Storage power stations	18’991	53.3 %		70.2 %
Mostly natural water supply	17’397	48.9 %	8’073	59.9 %
Partly pumped water supply	1’593	4.5 %	1’384	10.3 %
Pumped storage power stations	*1’326*		*316*	
Total (excl. pumped storage)	35’602	100.0 %	13’338	100.0 %

The capacity potential of hydropower in Switzerland is nearly exploited. The outlook of the Swiss Academy of Engineering Sciences (SATW) states that the hydroelectricity production of large-scale hydropower stations (>300 kW) will increase by 6% until 2050 (Berg & Real 2006). In future it is mainly the extension of existing power stations and the improvement of the technology that will lead to a growth in the production volume. At the same time, regulations of the residual flow will decrease the production potential (Frischknecht et al. 1996).

Compared to the large-scale hydropower, the growth potential of the electricity production from small hydropower stations is still significant. The Swiss Academy of Engineering Sciences (SATW) projects the amount of electricity produced in 2050 to be four times as much as today’s generation. According to their roadmap, the number of small hydropower stations will double till then (Berg & Real 2006).

1.2.2 Europe

In Europe, hydropower is an important energy source too. In the EU-27 countries, the electricity generated from hydropower has a share of 10 % of the total net electricity production (EUROSTAT 2010). In Austria and Norway the hydroelectricity accounts for even more than half of the net electricity production (see Tab. 1.2).

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[2] Bundesamt für Energie, April 2011: http://www.bfe.admin.ch/themen/00490/00491/00493/index.html?lang=de

Tab. 1.2: Hydropower electricity production and capacity in EU-27 countries (without pumped storage). Data are missing from Iceland, no hydropower generation in Malta and Cyprus (EUROSTAT 2010).

Country		**<1 MW**	**>1 MW - <10 MW**	**>10 MW**	**Share of total net electricity production**
Austria	Production (GWh)	1'637	3'179	33'129	60.5 %
	Capacity (MW)	454	725	7'040	
Belgium	Production (GWh)	26	207	176	0.5 %
	Capacity (MW)	9	50	52	
Bulgaria	Production (GWh)	108	417	2'299	6.9 %
	Capacity (MW)	39	191	1'890	
Croatia	Production (GWh)	1	94	5'121	44.2 %
	Capacity (MW)	1	32	1'749	
Czech Republic	Production (GWh)	492	475	1'057	2.6 %
	Capacity (MW)	151	141	753	
Denmark	Production (GWh)	12	14	-	0.1 %
	Capacity (MW)	5	4	-	
Estonia	Production (GWh)	28	-	-	0.3 %
	Capacity (MW)	5	-	-	
Finland	Production (GWh)	167	1'449	15'496	23.0 %
	Capacity (MW)	31	285	2'786	
France	Production (GWh)	1'582	5'342	56'802	11.6 %
	Capacity (MW)	455	1'604	18'823	
Germany	Production (GWh)	2'060	5'286	13'596	3.5 %
	Capacity (MW)	561	842	2'104	
Greece	Production (GWh)	117	207	2'987	5.6 %
	Capacity (MW)	44	114	2'319	
Hungary	Production (GWh)	16	34	163	0.6 %
	Capacity (MW)	4	10	37	
Ireland	Production (GWh)	47	85	836	3.4 %
	Capacity (MW)	23	20	196	
Italy	Production (GWh)	1'770	7'390	32'464	13.6 %
	Capacity (MW)	437	2'105	11'190	
Latvia	Production (GWh)	64	6	3'038	61.1 %
	Capacity (MW)	24	1	1511	
Lithuania	Production (GWh)	51	22	329	3.1 %
	Capacity (MW)	17	8	90	
Luxembourg	Production (GWh)	7	126	-	3.8 %
	Capacity (MW)	2	38	-	
Netherland	Production (GWh)	-	-	102	0.1 %
	Capacity (MW)	-	-	37	
Norway	Production (GWh)	235	5'402	133'917	98.6 %
	Capacity (MW)	48	1'048	27'150	
Poland	Production (GWh)	290	605	1'257	1.5 %
	Capacity (MW)	74	183	672	
Portugal	Production (GWh)	67	670	6'060	15.2 %
	Capacity (MW)	31	361	3'634	
Romania	Production (GWh)	99	549	1'6547	28.6 %
	Capacity (MW)	61	292	6009	
Slovakia	Production (GWh)	58	108	3'874	15.2 %
	Capacity (MW)	25	65	1'542	
Slovenia	Production (GWh)	264	193	3'561	26.2 %
	Capacity (MW)	117	37	873	

Spain	Production (GWh)	674	2'357	20'469	7.8 %
	Capacity (MW)	267	1'605	11'232	
Sweden	Production (GWh)	601	3'188	65'280	47.2 %
	Capacity (MW)	101	815	15'436	
Turkey	Production (GWh)	38	472	32'760	17.5 %
	Capacity (MW)	16	231	13'582	
United Kingdom	Production (GWh)	57	511	4'600	1.4 %
	Capacity (MW)	65	108	1'456	

1.2.3 World

The worldwide hydroelectricity generation amounts to 3.29 PWh (Tab. 1.4). Worldwide it is mainly North and South America with a high share on total electricity production (see Tab. 1.3 and Tab. 1.4) while, for example, the Middle East, with its dry climate, has a hydroelectricity production of a bit more than 1% of its total electricity production.

Tab. 1.3: Net electricity generation from hydropower and percentage of the total electricity production in different OECD countries of the world in 2010. Including pumped storage power production (IEA 2011).

Country	**Electricity production from hydropower (GWh)**	**Percentage to the total electricity production**
Australia	15'070	6.60 %
Brazil[3]	369'556	79.75 %
Canada	348'392	58.15 %
Japan	88'189	8.61 %
Korea	6'215	1.33 %
Mexico	36'109	14.67 %
New Zealand	24'765	58.13 %
United States	281'739	6.75 %

Tab. 1.4: Hydroelectricity generation and its percentage of the total electricity production in different regions of the world in 2008, including pumped storage power production[3].

Region	**Electricity production from hydropower (GWh)**	**Percentage to the total electricity production**
Africa	98’153	15.73 %
Asia excl. China	252’091	13.72 %
China	585’187	16.74 %
Latin America	673’862	63.02 %
Middle East	8’887	1.15 %
World	**3'287’554**	**16.23 %**

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[3] International Energy Agency, IEA, April 2011: http://www.iea.org/stats/prodresult.asp?PRODUCT=Electricity/Heat

2 Characterisation and description of the system

2.1 Power stations

2.1.1 Storage power stations

Storage power stations are power plants with an appreciable reservoir. Depending on the drop height it is distinguished between low, medium and high pressure power stations. The main focus in this study is on the latter ones.

The pumped storage power stations are a special type of storage power stations. While conventional storage power stations use water that comes from natural catchment areas higher up, the pumped storage power stations pump water up to reuse it. The share of pumped water to turbined water can reach up to 100 % (basic water flow plants). In this case the power plant has no natural supply of water. Often, storage hydropower stations are a mix of both, storage hydropower plants and pumped storage hydropower plants. Generally the different kinds of power plants differ more in the way they are operated than in the way they are built. Therefore the construction and deconstruction of storage hydropower stations and pumped storage hydropower stations are modelled identically, while the operation of storage and pumped storage hydropower plants is modelled separately. In this study, storage hydropower stations include all hydropower stations with a share of pumped water to turbined water of less than 100 % (see Tab. 2.1). Consequently it includes also hydropower stations that are commonly called pumped hydropower stations. The pumped storage hydropower stations modelled in this study only include basic water flow plants though. These are plants with no natural water supply. Following the two terms storage hydropower station and pumped storage hydropower station are used according to this definition.

Tab. 2.1: Classification of the hydropower stations.

Common naming	**Storage hydropower stations**	**Pumped storage hydropower stations**	**Basic water flow plants**
Share of pumped water to turbined water	0 %, only basic operation	< 100%	100%
Categories in this study	**Storage hydropower station**		**Pumped storage hydropower station**

The capacity of the reservoirs differs between the storage power stations: It can range from the storage capacity of water for a whole year down to only one day. Strictly speaking, even the run-of-river power stations have a small reservoir where the water is hold back. In this study the definition of storage power stations is made according to Frischknecht et al. (1996): Power stations with dams higher than 30 meters are classified as storage hydropower stations. This includes also a couple of high and medium pressure run-of-river power stations (BFE 2010b). Either are they part of clusters of power stations which are dominated by storage power plants or they are power stations with a small storage capacity (e.g. Amsteg, Croix). The first group of stations is left in the list of storage power plants, as it is not practical to separate single power stations from the cluster. The other group of run-of-river power stations could be added to the run-of-river power stations, but due to their construction they are more similar to storage power plants than to run-of-river hydropower stations.

The sample of storage hydropower stations (including pumped storage hydropower stations) considered in this study consists of 30 different groups with 52 dams. They are all situated in

Switzerland with an installed capacity of 8’565 MW and an expected net production of 16’639 GWh/a (BFE 2011c).

An average storage hydropower station is modelled in this study. It has a capacity of 95 MW and the expected net production is 190 GWh/a. The expected lifespan of 150 years is specified in Subchapter 2.5. Efficiencies are discussed in Subchapter 2.6. Detailed information about the storage hydropower stations is listed in Tab. 0.1 in the attachment.

2.1.2 Pumped storage power station

Pumped storage describes the circulation of water between a lower and an upper reservoir. It can run in a closed circuit where the water is pumped up in the hours with low electricity costs and turbined again when the demand and the costs for electricity are high. Pumped storage is also on hand, if the water is pumped up to a hydropower station to increase the inflow or for seasonal storage. In this study, only the hydropower stations with a closed circuit are considered as pumped storage hydropower stations. The others are included in the storage hydropower stations due to their similarities.

Depending on the altitude ratio of the pumping and the turbination of the water, there is either no net electricity generation (altitude ratio > 0.7) or the amount of net produced electricity corresponds to the difference between the electricity needed for pumping and the total electricity produced (altitude ratio < 0.7).

In the statistics of the hydropower stations the pumped storage power stations with a closed water circulation and no net electricity generation are not considered (BFE 2010b), the produced electricity is included in the statistics of electricity production though (BFE 2010a). The expected annual electricity generation of pumped storage is roughly 1’300 GWh (BFE 2011a, c), which represents 3.5 % of the total gross hydropower production in Switzerland. The yearly electricity consumption of the pumps is 1’657 GWh (BFE 2011a, c). This results in an efficiency of 0.8 (BFE 2011a). The pumping electricity stems partly from the hydropower stations themselves. However, the main part is drawn from the Swiss electricity mix. This is considered in the inventory in Section 4.2.2.

There are no standalone pumped storage power stations but they normally are integrated in a group of hydro power stations (storage and run-of-river power stations) sharing reservoirs and other infrastructures. Therefore it is not feasible to establish a separate inventory of the construction of pumped storage power stations. The inventory of the construction and deconstruction of the reservoirs is the same for storage power stations and the pumped storage power stations. The operation is inventoried separately.

2.1.3 Run-of-river power stations

The run-of-river power stations can also be divided into high, medium and low pressure power stations. The last category is the most common one including the power plants in rivers and canals.

As already mentioned above, some high pressure run-of-river hydropower stations are already taken into account in the list of the storage hydropower stations. The set of run-of-river power stations considered in this study is therefore mainly based on low pressure power plants.

Run-of-river power stations in Switzerland with an installed capacity of 3707 MW are considered. They have an expected annual net production of 16’611 GWh (BFE 2011c). The expected life span of the infrastructure and the machines is described in Subchapter 2.5. The efficiency of the run-of-river power stations is specified in Subchapter 2.6. The average run-of-river hydropower station modelled in this study has a capacity of 8.6 MW and the expected net production is 38.5 GWh/a.

2.2 Small hydropower stations

The category of small hydropower stations includes all the hydropower stations with a capacity below 300 kW (BFE 2010b). In other definitions hydropower stations with a capacity up to 1 MW are included[4]. A lot of them have been constructed during the industrialisation. First they were used as mechanical driving mechanism later they were converted to generate electricity. When the larger power stations were built and the production cost fell, the small hydropower stations were abandoned (Programm Kleinwasserkraftwerke 2010).

Due to action programmes of the Swiss Federal Office of Energy (SFOE) promoting renewable energy, the small hydropower stations have come back[5]. In 2008 small hydropower stations with a capacity of 760 MW and an annual production of 3'400 GWh were in operation[6]. They are situated in rivers and ravines but also in infrastructures such as drinking water supply systems, waste water treatment facilities, tunnels and the infrastructure for the production of artificial snow (Programm Kleinwasserkraftwerke 2010).

The small hydropower stations under study have a total capacity of 1.2 MW and a net production of 6.8 GWh/a (Baumgartner & Doka 1998; Jean-Baptiste & Konersmann 2000). They are located in rivers, in a drinking water supply system, in small ravines and in an irrigation system. The sample is divided into two groups: the power stations integrated in waterworks infrastructures and standalone hydropower stations (e.g. in rivers). This allows accounting for the differences in material consumption. The average small hydropower station modelled (in both groups) has a capacity of 193 MW and the expected net production is 1.1 GWh/a.

2.3 Specific properties of the alpine storage hydropower stations

Due to topographical, geological, climatic and hydrological differences as well as their state of technology, the hydropower plants in Switzerland are different from each other. There are no standards and each one has its own characteristics. In this study, a sample of 52 storage power stations is examined. The most important information is collected for all of them, whereas some specific aspects are investigated only on a few power stations and then extrapolated to the whole sample.

2.4 Temporal focus

The aim of this study is to analyse the environmental impacts of the Swiss hydroelectricity mix of today. Most of the Swiss hydro power stations have been erected between 1945 and 1970. As they still produce most of the hydropower electricity, it is not the latest technology that is described but the actual hydropower production mix.

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[4] Programm Kleinwasserkraftwerke, BFE, April 2011: http://www.bfe.admin.ch/kleinwasserkraft/index.html?lang=de

[5] Programm Kleinwasserkraftwerke, BFE, April 2011: http://www.bfe.admin.ch/kleinwasserkraft/index.html?lang=de

[6] Bundesamt für Energie, April 2011: http://www.bfe.admin.ch/themen/00490/00491/00493/index.html?lang=de

The life cycle inventory of hydropower is modelled as if its infrastructure is continuously replaced. Each kWh of electricity produced asks for a tiny fraction of the erection of the power plant.

It is assumed that in the early phase of hydropower development in Switzerland the most convenient locations have been used to build a power station (Frischknecht et al. 1996). Later projects are forced to use less accessible or less suited locations. There, the constructions are more complex and most often more material consuming. On the other hand, with the development of technologies, less material is used and more energy is generated. Those two trends tend to compensate each other, depending on the project.

2.5 Expected useful life

A decisive factor in quantifying the environmental impacts per kWh electricity is the technical lifespan of the power stations. The technical lifespan is assumed to be between the economic pay-back time and the actual lifespan. In Tab. 2.2, the approximated values of the economic and the technical lifespan are given for different parts in a hydropower station.

Tab. 2.2: Approximate values of the pay-back time and technical lifespan in years of different parts in a hydropower station (Engel et al. 1985).

Station/function unit	Pay-back time	Technical lifespan	Aspects to be considered
Construction			
Dams, tubes, tunnels, caverns, reservoirs, artificial lakes, surge chambers	60-80	80-150	Duration of water rights, quality, decay, security, losses
Buildings,	40-50	50-80	General conditions, wear, quality, state of the art, security, corrosion, maintenance
Water catchment, weir, pressure pipes, streets, bridges	40-50	40-60	
Mechanical parts			Security, losses, cavitation, erosion, corrosion, fatigue, reduction in efficiency, state of the art, quality, wear, load, construction
Kaplan turbine	30-40	30-60	
Pelton turbine	40-50	40-70	
Pump turbine	25-33	25-40	
Storage turbine	25-33	25-40	
Valves	25-40	25-50	
Cranes, other mechanical parts	20-40	25-50	
Electrical parts			Condition of the parts, cleanness, wear, security, quality, maintenance
Generators	25-40	30-60	
Transformers, high voltage facilities, other electrical facilities, monitoring system,	20-25	30-40	
Batteries	10-20	15-30	

The listed values tend to be conservative. This could result in an underestimation of the lifespans (Frischknecht et al. 1996): It is not expected that a reservoir shows major damages after 80-150 years of use (Sinniger et al. 1991). The outer layers of the dam might get minor damages due to frost and corrosion but it is possible to renovate them. The degradation of concrete is hardly severe enough to damage a dam severely. Earthquakes, flooding and glaciers are more capable to destroy a dam. The probability of these things to happen is, depending on the region, quite low though.

However, there is another factor to be considered: the siltation. While this can happen fast in small lakes (see e.g. artificial lake of Solis, completed in 1986[7]), big reservoirs are assumed to be fully functional for hundreds of years (Frischknecht et al. 1996).

In galleries, the concrete can be damaged too after a while depending on the water properties and composition of the concrete. In this case a renovation is needed. The service life of galleries can be longer than the one of reservoirs. In this case it is possible to turn a storage power plant with a reservoir where for example the process of siltation is already very advanced or even finished into an alpine run-of-river power station.

Depending on the type of turbine, their lifespan can be up to 300 years and more. This refers to the low-speed motors of run-of river power stations. Pelton turbines on the other hand can be worn by sand and the variations in the loading can lead to symptoms of fatigue. It can be cost-effective to change a turbine already before the end of its lifespan in order to improve the efficiency and by that the electricity production.

The above mentioned lifespans are summarised and averaged. The resulting values are shown in Tab. 2.3. All calculations in this study are based on these values.

Tab. 2.3: Average lifespan in years of different parts of a storage and run-of-river power stations (Frischknecht et al. 1996).

Parameter	**Storage power station**	**Run-of-river power station**
Concrete	200	80
Reinforcing steel	150	80
Steel (rest)	80	40
Copper	150[8]	80[8]
Explosives	250	100
Transport	150	60
Construction energy	150	80

2.6 Efficiency

There are different possible causes and places for losses in hydropower stations: Unused drop height, friction in the galleries and tubes and inefficiencies in the turbines.

The losses due to frictions are estimated to 5 % on average (Bischof 1992) while the turbines cause losses between 9 and 13 %, depending on their age. The efficiency of the generators has not increased very much: Modern generators reach 98 % and is only 2 % higher than the average of all the Swiss hydropower plants (König 1985). We assume that today the average efficiency of generators operated in hydroelectric power stations is 97 %.

Tab. 2.4 summarises the estimated efficiencies of modern power stations as well as of today's portfolio of hydropower stations in Switzerland.

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[7] http://www.stadt-zuerich.ch/solis, access on November 9, 2011

[8] Own assumption

Tab. 2.4: Average efficiency of run-of-river, storage and pumped storage hydropower stations in Switzerland (Bischof 1992; König 1985). Bold values are used in this study.

Part	**Average**	**Modern power stations**
Water works	0.95	0.95
Turbines	0.87	0.91
Generators	0.97	0.98
Transformers	0.98	0.99
Run-of-river power station (total)	**0.82**	**0.88**
Storage power station (total)		
Without water works	0.82	0.88
With water works	**0.78**	**0.84**
Pumped storage	**0.80**[9]	**0.8**

2.7 Functional unit

There is no linear relation between number and size of the reservoirs and the power stations. One power station can be fed by several lakes or there can be a reservoir that supplies several power stations on different levels. Therefore it is not practical to separate and allocate the material consumption and energy use to single power stations. Most often it is easier to consider a whole group of stations and reservoirs and to model an average hydropower station from this sample. This study focuses on a sample of 52 dams to represent the storage and pumped storage hydropower stations and on individual run-of-river power stations in Switzerland as well as on 6 small hydropower stations. From these samples, the material and energy input as well as the emissions of the construction, the operation and the deconstruction of the stations is modelled for an average hydropower station. The capacity and production of the average hydroelectric power plant is calculated using the Statistics of hydroelectric installations in Switzerland (BFE 2011c).

As mentioned before, the storage and the pumped storage hydropower stations are not examined separately in terms of their infrastructure. The infrastructure is a mix of both. It is only the electricity production (operation phase) that is differentiated.

The construction of run-of-river hydropower stations with and without reservoir are modelled identically (making use of the same infrastructure model). The operation of these two types is modelled separately to take into account the difference in land use and in emissions. They add up to the run-of-river hydropower stations with a capacity of 8.6 MW. This station represents the average run-of-river hydropower station mix in Switzerland.

Tab. 2.5 describes the characteristics of the different types of hydropower stations examined.

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[9] While the average efficiency of pumped storage hydropower stations was 0.7 in the national electricity statistics until 2009, it has been raised to 0.8 for 2010 (BFE 2011a)

Tab. 2.5: Characteristics for each type of hydropower station under study.

Hydropower station	Capacity (MW)	Expected annual net production (GWh)	Lifespan
Storage hydropower, electricity Pumped storage hydropower, electricity	95	190	150
Run-of-river hydropower	8.6	38.5	80
Small hydropower (integrated)	0.19	1.2	70
Small hydropower (standalone)	0.18	1.1	70

2.8 Hydrological and biological aspects

2.8.1 Introduction

This chapter describes the environmental impacts of the hydrological changes due to the construction and operation of hydropower plants. This text was initially written by Hans Müller-Lemans, Tergeso AG, Sargans and published in 1994 (Frischknecht et al. 1994).

The system is complex and the quantification and description of all processes and impacts is either an enormous effort or it leads to a biased picture, if only parts are considered. Even if it was possible to quantify all the influences, the focus on the hydrological implications of hydropower stations hinders the comparison with other energy systems where the focus lies on the material and energy demand and on the emissions caused by the energy and material supply and from the reservoirs.

As a consequence the hydrological and biological aspects are discussed only qualitatively in the following paragraphs. In order to include at least a couple of factors the following ones are quantified in the Sections 4.1.1-4.1.3 and 4.3.1-4.3.3: land use, useful capacity of the reservoir and turbined water.

2.8.2 Storage power stations

The storage power stations influence the natural system mainly at two points: the reservoir and the water catchment.

The **reservoirs** disrupt the natural flow of the water and, depending on the size of the reservoir, hold it back for a certain amount of time. Furthermore they are barriers for the actively migrating fishes and invertebrates and the organisms that are transported passively from upstream regions. Depending on the type of the water catchment, special constructions for the ascent of fishes and even invertebrates are available, but this kind of water catchments is not very common among the Swiss storage power stations. The construction of storage hydropower stations results in the flooding of pastures, forests, moors and rubble fields that can be part of valuable biotopes. The fluctuation of the water level inhibits the development of riverine vegetation and disfigures the landscape. Furthermore, the expanse of water can present a barrier for the migration of animals. They need to find new routes, often in impassable terrain.

The **water courses above the reservoirs** are cut from those below. For the storage power stations considered in this study, this concerns an area of 6’865 km^2 (Schweizerisches Talsperrenkomitee 2011).

The **residual flow reach** is highly influenced by the catchment and storage of the water. The amount of water released just beneath the dam is mainly given by the amount of water statutorily defined. Further downstream more factors influence the amount of water flowing: weather, geology, topography. The quality of the residual flow does not only depend on the amount of water but also on the properties of the streambed. The interrupt of the migration of fishes and invertebrates described above has an impact on the residual flow reach too. The storage power stations also interrupt the flow of coarse and fine grained organic substances that serve as nutrients downstream. The reduced peaks of the outflow lower the capacity of the water to transport the bed load. This might cause accumulations of rubble in the river bed. In summary, the storage power stations disturb the balance of solid matter in the river bed. This concerns mostly the temporal distribution as well as the grading of the solid matter transported.

The **stream** after the backflow of the turbined water is exposed to fluctuations in the volume of water due to temporal fluctuations in the electricity production. Fluctuations occur in a natural environment too. The biocoenosis is probably better adapted to fluctuations following natural rhythms and patterns than to artificial ones though.

2.8.3 Run-of-river hydropower stations

The **dams** of run-of-river hydropower stations disrupt the flowing waters. The consequences for fishes and invertebrates are described above. Depending on the type of dam, passage ways are available. Generally, the dams of run-of-river power stations are more easily conquerable than those of storage power stations. The transport of solid matter is mainly influenced by the spillway. The overflow is less favourable than the release at the bottom. Further impacts of the slack flow due to the dams are the following: The flow velocity decreases and this leads to the sedimentation of solid matter. The decomposition of the sediments consumes the oxygen and creates anoxic conditions. This process is supported by warmer water temperatures and a longer retention time of the water. Due to the sedimentation of particles the gravel in the riverbed is covered, which is unfavourable for species depending on gravel as spawning ground.

The parallel arrangement of the dams inhibits the settlement of a diverse biocoenosis. Only the availability of a wide range of biotopes enables the settlement of a wide range of biocoenosis.

Fishes can end up in the **turbined water** and get injured or killed. There are more or less successful ways to avoid that.

Residual flow reach is mainly found in run-of-river power stations built in channels. The problems of residual flow reaches are discussed above. They are influenced by the amount of water statutorily defined, the interactions between the ground water and the river and the structure of the river bed. In general, the problems of the residual flow reaches of run-of-river power stations are less severe than those of storage power stations.

In the sector of the **tail water**, erosion can be a consequence of the sedimentation above the dam. This leads to the recess of the riverbed. This can be avoided by the construction of barrages in the tail water. It is a general fact, that run-of-river hydropower stations disturb the transport of solid matter.

The **area around a run-of-river power station** is mainly influenced by the disruption due to the dam as well as by the consequent adjustments of the confluences of inflows. This affects the network of rivers and ravines and hinders fishes to use inflows as spawning grounds or as shelter during high water. The dams inhibit the overflow of biotopes that are dependent on the flooding with water and nutrients (e.g. floodplain forest). These biotopes have already been destroyed in earlier years by the measures of flood prevention though. The separation of the groundwater from the river has no immediate consequences, but it is an interference with the natural flow of the water bodies.

3 Construction of hydroelectric power stations

3.1 Introduction

In this Chapter the efforts and emissions related to the construction of the power stations are described. The main focus lies on the most important building materials such as cement, steel and explosives as well as on the transport and construction energy. In addition, the consumption of copper is quantified, which has been neglected in previous studies.

The demand in material and energy needed to construct power stations is related to the annual electricity produced. The system analysed includes the reservoirs, the dams and the associated buildings and the transformer. The distribution of the electricity is modelled in separate datasets.

3.2 Storage power station

In this Subchapter the life cycle inventory of the construction of an average storage hydropower station in Switzerland is described. The infrastructure is used for the generation of electricity by storage and pumped storage hydroelectric power plants. The term “plant” refers to the average hydropower station with the characteristics described in Tab. 2.5.

3.2.1 Cement, gravel and water

In terms of mass, gravel and cement are the most important building materials used in hydropower stations. They are used for the dams, the injections (cement only), the galleries and tunnels, the water catchment, the equalising reservoir, the buildings and the transport infrastructure.

The most prominent part of a storage power station is the dam. There are two different types of dams: the (concrete) dam and the barrage. As there are only few barrages in Switzerland, this study concentrates on the dams.

There are several types of dams and all of them can be found in Switzerland. Depending on the construction of those dams, the fraction of cement in the concrete varies from 140 to 300 kg/m^3. The average concentration of cement in concrete in the present sample is 230 kg/m^3 (see Tab. 0.1 in the Annex). Concrete is also used for injections into the underground of the dams for the sealing and contact of the construction. These injections mainly consist of concrete but there can also be additions of clay, smectite (bentonite), phosphate, aluminate and silicate. Additionally a considerable amount of concrete is used in galleries and tunnels. Depending on the function and construction of the tunnels, the amount of cement used per meter varies considerably. There are not much data available about the cement consumption in tunnels, neither about the construction of the buildings. Due to lack of data a rough estimation is done: With the available data of a few power stations an average ratio between the cement consumption in dams and the total amount of cement consumed is established. This ratio is applied to all other power stations of the sample and, based on their cement consumption for the dams, their total cement consumption is estimated. The resulting cement consumption is shown in Tab. 0.1 in the Annex.

Information sources used to quantify the cement consumption in storage hydropower stations are: Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), DesMeules (1961), Gicot (1956), KVR (1968), Link (1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961, 1971), Stucky (1962), Töndury (1956, 1964), Walther & Fetz (1963, 1971), Weber et al. (1965, 1970), Zingg (1961).

The total cement consumption and the average lifespan of 150 years for dams and 100 years for galleries and tunnels result in a cement consumption of **1.02*10^{8} kg/plant** (3.42 g/kWh).

Concrete is made using cement, gravel and water. 1 m^{3} of concrete consists of 0.8 m^{3} gravel, 0.127 m^{3} water and 0.073 m^{3} cement which is equivalent to 2’000 kg, 127 kg and 230 kg respectively (Bolliger & Bauer 2007). This results in a consumption of **5.65*10^{7} kg/plant** (1.89 g/kWh) of water and **8.89*10^{8} kg/plant** (29.8 g/kWh) of gravel.

3.2.2 Steel

Steel (construction steel, reinforcing steel and stainless steel) is the second most important material in terms of mass. Here, iron and cast iron is included in the total steel demand. Steel has a wide range of applications: Reinforcement, rock anchors, armoured tubes, pressure pipes, generators, transformers, turbines. Furthermore it is found in buildings and in the transport infrastructure.

The steel consumption varies even more between the different power stations and only few data are available. Information sources are Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963, 1971), Weber (1965, 1971) and other sources. A lifespan of 150 years is used for reinforcing steel and 80 years for the rest. The specific steel consumption is about 0.26 g/kWh. A specific amount of 0.06 g/kWh is allotted to reinforcing steel, 0.06 g/kWh to the machines and 0.14 g/kWh to the tubes and anchors etc. The consumption of the whole plant is **1.74*10^{6} kg/plant** of reinforcing steel, **1.82*10^{6} kg/plant** of chromium steel and **4.07*10^{6} kg/plant** of low-alloyed steel.

3.2.3 Copper

Copper is part of the turbines and generators as well as electric cables. According to Vattenfall (2008), the copper consumption in the infrastructure of a Swedish storage hydropower plant is 9.9*10^{-3} g/kWh. Applied on the power stations considered, this is a total amount of **2.96*10^{5} kg/plant**.

3.2.4 Explosives

Explosives are mainly used for the excavation of the fundament of the dam. Until 1970 also the galleries and tunnels have been blasted. Nowadays electric drilling machines are used.

As the consumption of explosives are approximately proportional to the amount of excavation, the measurement of the length and diameter of all the tunnels could be a basis to quantify the amount of explosives used. This is laborious though. The consumption of explosives is estimated based on the few data available (see Tab. 0.1). Information sources are Béguin et al. (1963), Bertschinger (1959), Blenio Kraftwerke (1968), Condrau (1962), KVR (1963, 1968), Töndury (1956, 1964), Weber et al. (1965) and other unpublished sources.

The average specific consumption of explosives is about 2*10^{-2} g/kWh. In total, it results in **5.95*10^{5} kg/plant**.

3.2.5 Transport

Most of the materials necessary to build the power stations need to be transported to the site. In Switzerland, transports are done by train as far as possible. The tonnage is dominated by the cement followed by the mass of the other materials: armoured tubes, reinforcing steel, construction machines etc. To be cost efficient, sand and gravel were gained from quarries as close to the site as possible. In some cases long distance transports were necessary. Further transports were caused by the excavated material.

From the closest railway station the transport was done by lorries. Often the streets leading to the construction site had to be built or expanded first. In some cases, the location of the site was inaccessible by road and a cableway was erected.

The transport is distinguished between the public transport network and the rest of the transport to the construction site. In the first case the transport itself is analysed and generic data are used to model the transport services. The second part is described via the energy consumption (fuel for lorries, electricity for cableways). This has two reasons: Firstly, the assessment of the wear of the streets and the noise does not have an effect outside of the public transport network. Secondly, it is assumed that the emission factors of the lorries do not apply under the conditions found on the routes leading to the construction site due to the steepness and impassibility of the streets.

Due to their locations and accessibility, the transport figures vary a lot between the power stations. The Bergeller Kraftwerke are analysed in a case study. The figures of the transport on the public transport network in Tab. 3.1 are based on the data of Bertschinger (1959):

Tab. 3.1: Transport services required during the construction of storage hydropower stations.

	Material	Specific transport distances		Total transport distances	
Train	Cement	$7.40*10^{-4}$	tkm/kWh	$2.21*10^{7}$	tkm/plant
	Other materials	$1.33*10^{-4}$	tkm/kWh	$3.98*10^{6}$	tkm/plant
	Total	$8.73*10^{-4}$	tkm/kWh	$2.61*10^{7}$	tkm/plant
Lorry	Cement	$1.13*10^{-4}$	tkm/kWh	$3.39*10^{6}$	tkm/plant
	Gravel and sand	$3.33*10^{-5}$	tkm/kWh	$9.96*10^{5}$	tkm/plant
	Other materials	$1.33*10^{-5}$	tkm/kWh	$3.98*10^{5}$	tkm/plant
	Total	$1.60*10^{-4}$	tkm/kWh	$4.78*10^{6}$	tkm/plant

The material is transported **$2.61*10^{7}$ tkm/plant** by train and **$4.78*10^{6}$ tkm/plant** by lorry.

3.2.6 Construction energy

The construction of hydropower stations is energy intensive. Energy is used in construction machines as well as for the transport of the material from the public transport network to the construction site (see also Section 3.2.5). In the following the consumption of electricity and fuel is described.

The electricity consumption sampled at the two sites Biasca and Linthal (Limmern) (see Tab. 0.1) amounts to an average specific value of $9.13*10^{-4}$ kWh/kWh. This results in the total electricity consumption of **$2.73*10^{7}$ kWh/plant**.

The specific use of fuel (mainly diesel) is around $4.67*10^{-2}$ g/kWh (Frischknecht et al. 1996). It is assumed that the diesel is used in average building machines. Applying an average calorific value of 42 MJ/kg this results in a total diesel consumption of **$5.97*10^{7}$ MJ/plant**.

More detailed information about the energy consumption for the construction of hydropower stations can be found in the following sources: Bertschinger (1959), Blenio Kraftwerke (1968), KVR (1968), Töndury (1964), Walther und Fetz (1963), Weber et al. (1965), BFE (1992) and other sources.

3.2.7 Particle emissions

Due to raised dust from blasting, excavations, vehicles on non-asphaltic streets and the preparation of concrete considerable amounts of particle emissions may be caused from the construction site of a hydropower station.

There is no specific information and data available about particle emissions during the construction of a storage hydropower station. As an approximation, the amount of the emissions is calculated according to the emission factors of general construction sites in Switzerland (BUWAL 2001, 2003). According to this source, an average of 500 kg PM10 is emitted per hectare, of which 15 % are PM2.5 emissions. The total amount of dust is 2’000 kg/ha. As a first approach, twice the area covered with the dam and other infrastructure (see Subchapter 4.1), 1.4 ha is considered. This results in total emissions of **103 kg** PM2.5, **2’063 kg** PM>10 and **584 kg** 2.5<PM<10. The construction of the storage power station emits a total amount of 2750 kg dust. This equals to 3.62*10^{-6} g of PM2.5, 6.90*10^{-5} g of PM>10 and 1.96*10^{-5} g of 2.5<PM<10 per kWh electricity produced.

3.3 Run-of-river power station

This Subchapter describes the construction of an average run-of-river hydropower station in Switzerland. Its characteristics are described in Tab. 2.5. The term “plant” refers to this hydropower station described.

3.3.1 Cement, gravel and water

It is expected that the average consumption of cement is lower for the run-of-river power stations than for the storage power station. As presented in Baumann (1949), Brux (1983), Herbeck und Reismann (1977), NOK (1956), Radag (1979) and others, the average is around 1.88 g/kWh. It results in a total consumption of **5.78*10^{6} kg/plant**. The consumption of gravel amounts to **5.03*10^{7} kg/plant** (16.3 g/kWh) and **3.19*10^{6} kg/plant** (1.04 g/kWh) of water is used.

3.3.2 Steel

Steel is to be found in different parts of a run-of-river power station. Apart from the use in generators and transformers, steel is also consumed for reinforcement, bulkheads, stop logs, screens, cranes and others.

The literature gives an average steel consumption of 30 g/(kWh/a) (Aegerter et al. 1954; Baumann 1949; Brux 1983; Erbiste 1984; Herbeck & Reismann 1977; NOK 1956; Radag 1979; Stambach 1944; Wunderle 1984). The power station Wildegg-Brugg (NOK 1956) suggests the following fractions for the different types of steel: 41 % reinforcing steel, 55 % low alloyed steel (tubes, anchors…) and 4 % chromium steel (machines). Averaged over a lifespan of 80 years for reinforcing steel and 40 years for the rest, the specific steel consumption is 0.6 g/kWh. The total amount of reinforcing steel in the run-of-river hydropower station is **4.73*10^{5} kg/plant** (0.15 g/kWh). The consumption of low-alloyed steel is **1.27*10^{6} kg/plant** (0.41 g/kWh) and of chromium steel it is **9.23*10^{4} kg/plant** (0.03 g/kWh).

3.3.3 Copper

Copper is used for turbines and generators as well as electric cables. It is assumed that the specific copper consumption of 9.9*10^{-3} g/kWh specified by Vattenfall (2008), is also valid for run-of-river hydropower stations. This results in a total amount of **3.05*10^{4} kg/plant**.

3.3.4 Explosives

Even though there are no tunnels to be built for run-of-river power stations, there are other purposes for which explosives are used: deepening of the river channel, removing big rocks and mining of boulders. The amount used is estimated based on Bolliger and Bauer (2007), where the specific consumption for the construction of the power station Wildegg-Brugg is reported to be $6.3*10^{-4}$ g/kWh. Applied on the average power plant under study, this is **$1.94*10^{3}$ kg/plant**.

3.3.5 Transport

There are hardly any data available for the transport services required to ship the material to the site. Estimations based on Frischknecht et al. (1996) give values around $1.90*10^{-4}$ tkm/kWh for the transport by lorry as well as by train. This results in transport services of **$5.84*10^{5}$ tkm/unit**.

3.3.6 Construction energy

Energy is needed to run the different construction machines as well as for the transport of the construction materials and the excavated material. On-site, the transport is often carried out by trucks. In earlier years steam locomotives with coal fuel firing were used.

Information about the electricity and fuel consumption is found in Baumann (1949), NOK (1956) and Wunderle (1984). The specific energy consumption is $5.0*10^{-4}$ kWh/kWh of electricity and 0.11 g/kWh of diesel. Applied on the whole plant, it results in a electricity consumption of **$1.54*10^{6}$ kWh/plant**. The consumption of diesel amounts to **$1.45*10^{7}$ MJ/plant**.

3.3.7 Particle emissions

There is not information on the particle emissions due to the construction of run-of-river power stations in Switzerland. It can be assumed that, in comparison to the storage power stations, the emissions are lower as parts of the excavation work is taking place under water and as the dams are smaller.

As an approximation, the amount of the emissions is calculated according to the emission factors of general construction sites in Switzerland (BUWAL 2001, 2003). It is specified that per hectare of area under construction a total amount of 2’000 kg dust is emitted. 500 kg of it is PM10. Of the total PM10 emissions another 15 % is classified as PM2.5. For the application of these factors to the run-of-river power stations under study, a total construction area of 0.34 ha is assumed. This corresponds to twice the area classified as “industrial area, built up” (see Section 4.3.1). The particle emissions amount to: **$2.58*10^{1}$ kg/plant** PM<2.5, **$5.17*10^{2}$ kg/plant** PM>10 and **$1.46*10^{2}$ kg/plant** 2.5<PM<10. Per kWh of produced electricity the dust emissions consist of $8.40*10^{-9}$ kg PM<2.5, $1.68*10^{-7}$ kg PM>10 and $4.76*10^{-8}$ kg 2.5<PM<10.

3.4 Small hydropower stations

This Subchapter describes the construction of two types of small hydropower stations in Switzerland. One station is integrated in waterworks infrastructure the other one is a standalone small hydropower station. The term “plant” refers to the respective hydropower station as described in Tab. 2.5.

3.4.1 Small hydropower stations integrated in waterworks

The material consumption figures of the small hydropower stations integrated in waterworks infrastructures are based on Baumgartner and Doka (1998) and on Jean-Baptiste and Konersmann (2000).

The sample of small hydropower stations integrated in waterworks infrastructure has an average specific consumption of 1.49 g/kWh of concrete, which is in total **1.21*10^5 kg/plant** or 55.2 m^3/plant, respectively. Additionally **5.21*10^5 kg/plant** (6.41 g/kWh) gravel is used. Both materials are mainly used for the pipes and high pressure pipes for the water supply.

The construction of the water supply consumes steel as well. Reinforcing steel is also used for the buildings and the generators. The total amount consumed is **2.12*10^3 kg/plant** (2.60*10^{-2} g/kWh).

1.01*10^3 kg/plant and **1.31*10^3 kg/plant** of chromium steel and low-alloyed steel, respectively, are used in the turbines and the generators. This is based on the average specific consumption of 1.24*10^{-2} g/kWh of chromium steel and 1.62*10^{-2} g/kWh of low-alloyed steel.

Polyethylene (PE) and polyvinylchloride (PVC) are further materials used in the construction of the water supply. The small hydropower stations integrated in waterworks infrastructures have a total consumption of **8.52*10^3 kg/plant** (1.05*10^{-1} g/kWh) of PE and **1.24*10^3 kg/plant** (1.52*10^{-2} g/kWh) of PVC.

High pressure pipes consist of cast iron. With an average weight of 50 kg per meter of pipe (Jean-Baptiste & Konersmann 2000) and 2’290 m of length, the total amount of cast iron used is **4.67*10^4 kg/plant** (5.74*10^{-1} g/kWh).

The total copper consumption amounts to **2.18*10^2 kg/plant** (2.68*10^{-3} g/kWh). Copper is used in the turbines, generators, the electric devices as well as in the high pressure pipes.

In the material inventory of the hydropower stations described by Baumgartner and Doka (1998), there is a category “miscellaneous”. No further information on this category is available. Based on the study of Jean-Baptiste and Konersmann (2000), the consumption of aluminium, lead, steel panel, glass, argon and wood as well as the amount of waste and waste water is modelled based on the ratio of the average material use per average capacity (kW) of the power station. The factors are only applied to the power stations described by Baumgartner and Doka (1998). The original data are used to model the power stations of Jean-Baptiste and Konersmann (2000). In Tab. 3.2 the modelling factors as well as the resulting average and total consumptions are listed.

Tab. 3.2: Factors for the modelling of the consumption of different materials of small hydropower stations integrated in waterworks infrastructure. The factors are based on the average material use per average capacity (Jean-Baptiste & Konersmann 2000).

Material	**Factor**	**Specific consumption**	**Total consumption**
	kg/kW	g/kWh	kg/plant
Aluminum	0.14	$2.98*10^{-4}$	24.2
Lead	0.08	$1.70*10^{-4}$	13.9
Steel panel	0.44	$6.49*10^{-4}$	52.7
Glass	0.003	$1.23*10^{-5}$	1.00
Argon	0.03	$7.20*10^{-5}$	5.85
Wood (**m^3**) [1])	0.14	$3.84*10^{-10}$	$3.12*10^{-2}$
Tap water	24'034	$4.96*10^{1}$	$4.03*10^{6}$
Waste	0.06	$1.14*10^{-4}$	9.25
Waste water [1])	0.01	$1.97*10^{-8}$	1.60

[1]): in m^3/kW; m^3/kWh; m^3/plant

The consumption of diesel and electricity during the construction of the power stations is **$6.27*10^3$ MJ/plant** ($7.72*10^{-5}$ MJ/kWh) and **$7.67*10^2$ kWh/plant** ($9.44*10^{-6}$ kWh/kWh), respectively. .

The amount of transport services needed is based on the standard distances of Frischknecht et al. (2007).

3.4.2 Standalone small hydropower stations

The material consumption of the small hydropower stations is based on Baumgartner and Doka (1998) and Axpo (2008). The data are complemented with information from Jean-Baptiste and Konersmann (2000).

On average, the sample of small hydropower stations consumes 17.9 g/kWh of concrete, which is in total **$1.39*10^6$ kg/plant** or $6.30*10^2$ m^3/plant, respectively. Furthermore, **$1.11*10^6$ kg/plant** (14.3 g/kWh) of gravel is used. The concrete and the gravel are used for the construction of pipes and high pressure pipes in the water supply.

Steel is also consumed for the construction of the water supply. Reinforcing steel is used for the buildings and the generators. Per kWh electricity produced $6.44*10^{-1}$ g of reinforcing steel is consumed. The total amount is **$4.99*10^4$ kg/plant**.

The turbines and generators consume a total of **$5.33*10^2$ kg/plant** ($6.87*10^{-3}$ g/kWh) and **$1.39*10^3$ kg/plant** ($1.79*10^{-2}$ g/kWh) of chromium steel and low-alloyed steel, respectively.

The small hydropower stations have an average specific consumption of $1.17*10^{-1}$ g PE/kWh and $2.51*10^{-2}$ g PVC/kWh. Both materials are used in the water supply. In total this is **$9.05*10^3$ kg/plant** of PE and **$1.95*10^3$ kg/plant** of PVC.

The hydropower stations have high pressure pipes with a total length of 815 m. They consist of cast iron and have a weight of 50 kg per meter (Jean-Baptiste & Konersmann 2000). Consequently, a total of **$2.72*10^4$ kg/plant** of cast iron is consumed, which results in a specific demand of $3.50*10^{-1}$ g/kWh.

Copper is generally used in electric devices. Furthermore it is used in the turbines, the generators and the high pressure pipes. The total consumption of the power stations under study is **$2.08*10^2$ kg/plant** ($2.68*10^{-3}$ g/kWh).

The category “miscellaneous” in the inventory of Baumgartner and Doka (1998) is not further specified. Therefore, the consumption of aluminium, lead, steel panel, glass, argon and wood as well as the amount of waste and waste water is modelled based on the ratio of the average material use per average capacity (kW) of the power station in the study of Jean-Baptiste and Konersmann (2000). In Tab. 3.3 the modelling factors as well as the resulting average and total consumptions are listed.

Tab. 3.3: Factors for the modelling of the consumption of different materials of standalone small hydropower stations. The factors are based on the average material use per average capacity (Jean-Baptiste and Konersmann 2000).

Material	**Factor**	**Specific consumption**	**Total consumption**
unit	kg/kW	g/kWh	kg/plant
Aluminum	0.14	$3.45*10^{-4}$	26.8
Lead	0.08	$2.09*10^{-4}$	16.2
Steel panel	0.44	$1.09*10^{-3}$	84.5
Glass	0.003	$7.26*10^{-6}$	0.56
Argon	0.03	$8.67*10^{-5}$	6.73
Wood (**m**^{3}) 1)	0.14	$4.63*10^{-10}$	$3.59*10^{-2}$
Tap water	24'034	$5.97*10^{1}$	$4.63*10^{6}$
Waste	0.06kg/kW	$1.37*10^{-4}$	10.6
Waste water 1)	0.01m3/kW	$2.37*10^{-8}$	1.84

1): in m^{3}/kW; m^{3}/kWh; m^{3}/plant

The consumption of diesel and electricity during the construction of the power stations is **5.33*10^{4} MJ/plant** (6.87*10^{-4} MJ/kWh), and **1.02*10^{3} kWh/plant** (1.31*10^{-5} kWh/kWh), respectively.

The amount of transport services needed is based on the standard distances of Frischknecht et al. (2007).

3.5 Data quality

For the storage power stations, most of the data are based on information of the whole or parts of the sample under study. The temporal and geographic correlation is good. The technology described is the same as well. As the original data of the construction of the storage power stations are not directly accessible, a basic uncertainty is given. It is increased due to missing data and, for some inputs and emissions, the limited number of data samples. Information on the copper consumption is derived from other power stations that are not part of the sample under study. It can be assumed though that the technology is similar and that the geographic differences do not influence the specific demand significantly. The modelling of the particle emissions is not based on the same application and neither on the same geographic conditions, which adds to the uncertainty. In general, the quality of the data is good. The data are well suited to describe the system under study. More detailed investigations are mainly needed for the construction energy (electricity and diesel) and the transport services required as well as the particle emissions.

Specific figures necessary for the modelling of the construction phase of the run-of-river power station are adopted from earlier studies (Bolliger & Bauer 2007; Frischknecht et al. 1996) and the original information sources are not available. This leads to a significant uncertainty. The data are derived from some power stations under study and this provides a satisfying correlation in terms of geography, temporal aspects and technology though. On the other hand, the data-sets do not describe the whole set of power stations under study, therefore the data-sets are not complete and the necessary extrapolations increase the general uncertainty. The particle emissions are modelled based on data from another application (general construction sites), which leads to uncertainties. In general, the data are well suited to describe the system under study.

The original data of the small hydropower stations integrated in existing waterworks infrastructure are very detailed and accurate. The sample size of the small hydropower stations for both groups is rather small though and possible outliers get more weight. This leads to a rather high uncertainty. There is a good correlation regarding technology, geography as well as temporal aspects though. Certain assumptions were needed for the standalone small hydropower stations, which increases the uncertainties. Further investigations on the material requirements and the construction efforts of small hydropower stations are recommended.

3.6 Life Cycle inventories of the construction of hydropower plants

In this Subchapter the unit process raw data of the construction of the hydropower plants are presented.

Tab. 3.4: Unit process raw data of reservoir hydropower plant/CH.

	Name	Location	Unit	reservoir hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			1			
	Unit			unit			
product	reservoir hydropower plant	CH	unit	1			
technosphere	chromium steel 18/8, at plant	RER	kg	1.82E+6	1	1.24	(4,3,1,1,1,4,BU:1.05); Turbines and generators; recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	diesel, burned in building machine	GLO	MJ	5.97E+7	1	1.24	(4,3,1,1,1,4,BU:1.05); Fuel for construction machines; based on Frischknecht et al. (1996)
	explosives, tovex, at plant	CH	kg	5.95E+5	1	1.24	(4,3,1,1,1,4,BU:1.05); Tunnels and galleries; recalculated based on Béguin et al. 1963, Bertschinger 1959, Blenio Kraftwerke 1968, Condrau 1962, KVR 1963; 1968, Töndury 1956; 1964, Weber et al. 1965 and other sources.
	gravel, round, at mine	CH	kg	8.89E+8	1	1.24	(3,5,1,1,1,2,BU:1.05); Concrete for dams, buildings and other infrastructure; recalculated based on Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), Des Meules (1961), Gicot (1956), KVR (1968), Link(1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961; 1971), Stucky (1962), Töndury (1956; 1964), Walther & Fetz (1963; 1971), Weber et al. (1965; 1970), Zingg(1961).
	cement, unspecified, at plant	CH	kg	1.02E+8	1	1.24	(3,5,1,1,1,2,BU:1.05); Concrete for dams, buildings and other infrastructure; recalculated based on Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), Des Meules (1961), Gicot (1956), KVR (1968), Link(1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961; 1971), Stucky (1962), Töndury (1956; 1964), Walther & Fetz (1963; 1971), Weber et al. (1965; 1970), Zingg(1961).
	reinforcing steel, at plant	RER	kg	1.74E+6	1	1.24	(4,3,1,1,1,4,BU:1.05); Buildings and other infrastructure; recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	steel, low-alloyed, at plant	RER	kg	4.07E+6	1	1.24	(4,3,1,1,1,4,BU:1.05); Tubes and pipes; recalculated based on recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	copper, at regional storage	RER	kg	2.96E+5	1	1.34	(3,5,1,5,1,5,BU:1.05); Electric cables; Vattenfall (2008)
	tap water, at user	CH	kg	5.65E+7	1	1.24	(3,5,1,1,1,2,BU:1.05); Concrete for dams, buildings and other infrastructure; recalculated based on Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), Des Meules (1961), Gicot (1956), KVR (1968), Link(1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961; 1971), Stucky (1962), Töndury (1956; 1964), Walther & Fetz (1963; 1971), Weber et al. (1965; 1970), Zingg(1961).
	electricity, medium voltage, at grid	CH	kWh	2.73E+7	1	1.24	(4,3,1,1,1,4,BU:1.05); Electricity supply for the construction; recalculated based on Bertschinger (1959), Blenio Kraftwerke (1968), KVR (1968), Töndury (1964), Walther und Fetz (1963), Weber et al. (1965), BFE (1992) and other sources.
	disposal, building, reinforced concrete, to recycling	CH	kg	5.79E+7	1	1.24	(4,3,1,1,1,4,BU:1.05); Recycling of reinforced infrastructure; based on Frischknecht (1996), assumed recycling rate: 100%
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	9.36E+8	1	1.24	(4,3,1,1,1,4,BU:1.05); Non-inforced infrastructure left on-site at the end of the use phase of the power station (especially the dams, tunnels, galleries); based on Frischknecht et al. (1996)
	disposal, building, reinforcement steel, to recycling	CH	kg	5.88E+6	1	1.24	(4,3,1,1,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; assumed recycling rate: 100%
	transport, lorry 20-28t, fleet average	CH	tkm	4.78E+6	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Bertschinger (1959)
	transport, freight, rail	CH	tkm	2.61E+7	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Bertschinger (1959)
emission air, low population	Heat, waste	-	MJ	9.82E+7	1	1.24	(4,3,1,1,1,4,BU:1.05); From electricity
	Particulates, < 2.5 um	-	kg	1.03E+2	1	3.61	(4,5,5,5,4,5,BU:3); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 10 um	-	kg	2.06E+3	1	2.17	(4,5,5,5,4,5,BU:1.5); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 2.5 um, and < 10um	-	kg	5.84E+2	1	2.61	(4,5,5,5,4,5,BU:2); Particle emissions during the construction; based on BUWAL (2001, 2003)

Tab. 3.5: Unit process raw data of run-of-river hydropower plant/CH.

	Name	Location	Unit	run-of-river hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			1			
	Unit			unit			
product	run-of-river hydropower plant	CH	unit	1			
technosphere	chromium steel 18/8, at plant	RER	kg	9.23E+4	1	1.27	(4,3,3,1,1,4,BU:1.05); Turbines and generators; based on Frischknecht et al. (1996) and Bauer et al. (2007)
	diesel, burned in building machine	GLO	MJ	1.45E+7	1	1.40	(4,5,3,1,1,5,BU:1.05); Fuel for building machines; recalculated based on Frischknecht et al. (1996)
	explosives, tovex, at plant	CH	kg	1.94E+3	1	1.40	(4,5,3,1,1,5,BU:1.05); Tunnels and galleries; based on Bauer et al. (2007)
	gravel, round, at mine	CH	kg	5.03E+7	1	1.27	(4,3,3,1,1,4,BU:1.05); Concrete for buildings and other infrastructure; recalculated based on Frischknecht et al. (1996)
	cement, unspecified, at plant	CH	kg	5.78E+6	1	1.27	(4,3,3,1,1,4,BU:1.05); Concrete for buildings and other infrastructure; recalculated based on Frischknecht et al. (1996)
	reinforcing steel, at plant	RER	kg	4.73E+5	1	1.27	(4,3,3,1,1,4,BU:1.05); Buildings and other infrastructure; based on Frischknecht et al. (1996) and Bauer et al. (2007)
	steel, low-alloyed, at plant	RER	kg	1.27E+6	1	1.27	(4,3,3,1,1,4,BU:1.05); Tubes and pipes; based on Frischknecht et al. (1996) and Bauer et al. (2007)
	copper, at regional storage	RER	kg	3.05E+4	1	1.52	(4,5,4,5,3,5,BU:1.05); Electric cables; calculated based on Vattenfall (2008)
	tap water, at user	CH	kg	3.19E+6	1	1.27	(4,3,3,1,1,4,BU:1.05); Concrete for buildings and other infrastructure; recalculated based on Frischknecht et al. (1996)
	electricity, medium voltage, at grid	CH	kWh	1.54E+6	1	1.40	(4,5,3,1,1,5,BU:1.05); Electricity supply for the construction; recalculated based on Frischknecht et al. (1996)
	disposal, building, reinforced concrete, to recycling	CH	kg	1.58E+7	1	1.27	(4,3,3,1,1,4,BU:1.05); Recycling of reinforced infrastructure (especially buildings); recalculated based on Frischknecht et al. (1996), assumed recycling rate: 100%
	disposal, building, reinforcement steel, to recycling	CH	kg	1.36E+6	1	1.27	(4,3,3,1,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; recalculated based Frischknecht et al. (1996), assumed recycling rate: 100%
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	4.08E+7	1	1.27	(4,3,3,1,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; recalculated based Frischknecht et al. (1996), assumed recycling rate: 100%
	transport, lorry 20-28t, fleet average	CH	tkm	5.84E+5	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; Based on Frischknecht et al. (1996)
	transport, freight, rail	CH	tkm	5.84E+5	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Frischknecht et al. (1996)
emission air, low population density	Heat, waste	-	MJ	5.54E+6	1	1.40	(4,5,3,1,1,5,BU:1.05); From electricity; based on Frischknecht et al. (1996)
	Particulates, < 2.5 um	-	kg	2.58E+1	1	3.61	(4,5,5,5,4,5,BU:3); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 10 um	-	kg	5.17E+2	1	2.17	(4,5,5,5,4,5,BU:1.5); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 2.5 um, and < 10um	-	kg	1.46E+2	1	2.61	(4,5,5,5,4,5,BU:2); Particle emissions during the construction; based on BUWAL (2001, 2003)

Tab. 3.6: Unit process raw data of small hydropower plant, in waterworks infrastructure/CH and small hydropower plant/CH.

	Name	Location	Unit	small hydropower plant, in waterworks infrastructure	small hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH	CH			
	InfrastructureProcess			1	1			
	Unit			unit	unit			
product	small hydropower plant, in waterworks infrastructure	CH	unit	1	0			
	small hydropower plant	CH	unit	0	1			
technosphere	concrete, normal, at plant	CH	m3	5.52E+1	6.30E+2	1	1.24	(4,1,3,1,1,3,BU:1.05); Infrastructure; literature
	gravel, round, at mine	CH	kg	5.21E+5	1.11E+6	1	1.24	(4,1,3,1,1,3,BU:1.05); Infrastructure; literature
	reinforcing steel, at plant	RER	kg	2.12E+3	4.99E+4	1	1.24	(4,1,3,1,1,3,BU:1.05); Infrastructure; literature
	chromium steel 18/8, at plant	RER	kg	1.01E+3	6.18E+2	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbines, generator, switchboard; literature
	steel, low-alloyed, at plant	RER	kg	1.31E+3	1.39E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbines, generator; literature
	copper, at regional storage	RER	kg	2.18E+2	2.08E+2	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbine, generatior and switchboard; literature
	polyethylene, HDPE, granulate, at plant	RER	kg	8.52E+3	9.05E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); Water pipes; literature
	polyvinylchloride, at regional storage	RER	kg	1.24E+3	1.95E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); Water pipes; literature
	cast iron, at plant	RER	kg	4.67E+4	2.72E+4	1	1.24	(4,1,3,1,1,3,BU:1.05); Water pipes; literature
	aluminium, production mix, at plant	RER	kg	2.42E+1	2.68E+1	1	1.24	(4,1,3,1,1,3,BU:1.05); Switchboard; literature
	lead, at regional storage	RER	kg	1.39E+1	1.62E+1	1	1.24	(4,1,3,1,1,3,BU:1.05); Switchboard; literature
	flat glass, uncoated, at plant	RER	kg	9.96E-1	5.63E-1	1	1.24	(4,1,3,1,1,3,BU:1.05); Switchboard; literature
	argon, liquid, at plant	RER	kg	5.85E+0	6.73E+0	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	sawn timber, softwood, raw, plant-debarked, u=70%, at plant	RER	m3	3.12E-2	3.59E-2	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	tap water, at user	CH	kg	4.03E+6	4.63E+6	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbiens; literature
	diesel, burned in building machine	GLO	MJ	6.27E+3	5.33E+4	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	electricity, medium voltage, at grid	CH	kWh	7.67E+2	1.02E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	transport, lorry 20-28t, fleet average	CH	tkm	1.59E+4	5.45E+4	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials and waste
	transport, freight, rail	CH	tkm	3.28E+4	4.98E+4	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials and waste
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	kg	9.25E+0	1.06E+1	1	1.24	(4,1,3,1,1,3,BU:1.05); From turbines; literature
	treatment, sewage, to wastewater treatment, class 3	CH	m3	1.60E+0	1.84E+0	1	1.24	(4,1,3,1,1,3,BU:1.05); From turbines; literature
	disposal, building, reinforced concrete, to recycling	CH	kg	7.05E+4	1.43E+6	1	1.24	(4,1,3,1,1,3,BU:1.05); From infrastructure; literature
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	5.31E+4		1	1.24	(4,1,3,1,1,3,BU:1.05); From infrastructure; literature
	disposal, building, concrete gravel, to final disposal	CH	kg	5.21E+5	1.11E+6	1	1.24	(4,1,3,1,1,3,BU:1.05); From infrastructure; literature
	disposal, building, reinforcement steel, to recycling	CH	kg	2.32E+3	9.05E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); From turbines, generators, switchboards; literature
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	kg	8.52E+3	9.05E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); From water pipes; literature
	disposal, polyvinylchloride, 0.2% water, to municipal incineration	CH	kg	1.24E+3	1.95E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); From water pipes; literature
	disposal, building, bulk iron (excluding reinforcement), to sorting plant	CH	kg	4.67E+4	2.72E+4	1	1.24	(4,1,3,1,1,3,BU:1.05); From water pipes; literature
	disposal, glass, 0% water, to municipal incineration	CH	kg	9.96E-1	5.63E-1	1	1.24	(4,1,3,1,1,3,BU:1.05); From switchboards; literature
	disposal, wood untreated, 20% water, to municipal incineration	CH	kg	2.39E+1	2.75E+1	1	1.24	(4,1,3,1,1,3,BU:1.05); From turbines; literature
emission air, low population density	Heat, waste	-	MJ	7.67E+2	1.02E+3	1	1.24	(4,1,3,1,1,3,BU:1.05); From electricity

4 Operation of the hydroelectric power stations

In this Chapter the emissions, working material consumption during the operation of the different hydroelectric power stations are described. The specifications "per plant" refer to the operation of one plant over its lifespan.

The potential energy of the water is calculated from the efficiency of the generators (0.97) and transformators (0.98) and amounts to 3.79 MJ/kWh. It is the same for all types of hydropower stations described. The exceptions are the pumped storage hydropower stations where the potential energy is not considered.

4.1 Storage power station

4.1.1 Land use

The largest part of the land use of storage power stations is due to the reservoirs. The water floods pastures, swamps, rocks etc. and transforms them to water courses and artificial lakes. The average reservoir of the storage power stations in the sample covers a total area of $1.16*10^6$ m^2/plant[10]. This results in a land transformation of **$2.41*10^{-5}$ m^2/kWh** electricity produced. The reservoir of the average storage hydropower station modelled in this study covers a total of $7.21*10^5$ m^2. This corresponds to a land occupation of the water bodies of $3.62*10^{-3}$ m^2a/kWh.

These values correspond to the surface area of the reservoirs. Considering the ground area being larger than its surface, the actual amount of land and biotopes covered by the reservoirs is even higher. There is no information about the ground area available though, further investigations would be needed.

The area covered by buildings and other infrastructures is minor compared to the reservoirs. This is especially true, as they are often built into the rocks and therefore they do not use surface area. Following Frischknecht et al. (1996), 1 % of the area covered by the reservoirs is added and assigned to the dams, streets, buildings etc.

The initial state of the area used is characterised as "**unknown**" because of the variety between the different sites: moorlands, pastures, forests, rocky ravines and even small villages. Due to the lack of data it is impossible to model the exact initial state and the ecological value of each flooded area.

The state of the flooded area during the operation of the power stations is characterised as "**water bodies, artificial**". The infrastructure around the reservoirs (dams, buildings etc.) is modelled as "**industrial area, built up**".

4.1.2 Useful capacity of the reservoirs

The volume of the reservoirs is not only important for the water management but also because of ecological aspects. Reservoirs withdraw the water from its natural circulation for a certain amount of time. The volume influences the water discharge in terms of the amount as well as the time of the release, depending on the type of reservoir.

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[10] Schweizerische Talsperrenkomitee, March 2011: http://www.swissdams.ch/Dams/damList/default_d.asp?Sort=NomAsc

The fluctuation of the water level and the exposed stripes of land on the water's edge are influenced by the volume of the reservoir too. The fluctuation of the water level might be of climatic relevance especially in the tropics as the climatic conditions favour a rapid plant cover of the stripes. When the stripes are flooded again, the biomass is decomposed under relatively warm and often anaerobic conditions in shallow waters which can lead to emissions of greenhouse gases, especially methane (dos Santos et al. 2006; Fearnside 2004). Greenhouse gas emissions are discussed and quantified in Section 4.1.6.

On average, a storage hydropower station has a total reservoir volume of $3.27*10^7$ m^3.[11] This results in a specific volume of **$1.09*10^{-3}$ m^3/kWh**.

4.1.3 Water use and consumption

The amount of turbined water equals the amount of water withdrawn from its natural circulation minus losses. The specific amount of turbined water (**1.40 m^3/kWh**) gives no direct information about its ecological impact though. It is rather a physical relationship between the head and the volume of the water. Nevertheless it gives an indication of the amount of water temporarily withdrawn from the natural environment.

The average storage power station turbines a total amount of $4.19*10^{10}$ m^3 water during its lifespan (Tab. 0.1) (BWW 1973).

While the turbined water is released back to the original watershed after the use, water that evaporates from the reservoir is lost to the ecosystem. This is defined as water consumption.

The water evaporated from reservoirs is estimated based on an average annual evaporation in Switzerland. It amounts to 484 mm (Spreafico & Weingartner 2005). In combination with the specific reservoir surface area of $2.41*10^{-5}$ m^2/kWh, this results in a specific evaporation of **1.75 kg/kWh**. It is listed as air emission "water, CH".

4.1.4 Electricity use

Pumps are not only used in pumped storage hydropower stations but also in storage power stations (e.g. as loader). Of the total annual pump electricity consumption of 2'494 GWh (BFE 2011a), 573 GWh are used in Swiss storage hydropower stations for such pumps and 263 GWh are used in hydropower plants that partly operate as pumped storage hydropower stations (BFE 2011c). This is an annual electricity consumption of storage hydropower stations of 835 GWh. The rest, 1'657 GWh, is consumed in pumped storage hydropower stations (basic water flow plants only). With an annual electricity production of 18'991 GWh by storage hydropower stations (BFE 2011c), **0.044 GWh** electricity is used per GWh electricity produced.

4.1.5 Use of lubricating oil

A study of Vattenfall (2008) indicates that their storage hydropower stations emit **$2.27*10^{-5}$ g/kWh** lubricating oil to the water and **$9.76*10^{-6}$ g/kWh** to the ground. Applied to the average power plant under study, this results in a loss of $6.78*10^2$ kg/plant to the water and $2.92*10^2$ kg/plant to the ground over the whole lifespan. The same amounts are included as material input to the operation of the storage hydropower station.

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[11] Schweizerische Talsperrenkomitee, March 2011: http://www.swissdams.ch/Dams/damList/default_d.asp?Sort=NomAsc

4.1.6 Greenhouse gas emissions

Measurements and studies on various reservoirs have shown that artificial lakes emit a substantial amount of greenhouse gases (Diem et al. 2008) . There are several processes that may lead to the emission of those gases from reservoirs: The aerobic and anaerobic decomposition of organic matter that is flooded due to the construction of a reservoir, the nutrient inflow from upstream, plants and plankton growing in the water, vegetation that quickly grows on exposed land around the shore, when the water level is low, and is flooded again when the water rises (Fearnside 2004; Mäkinen & Khan 2010).

To get an accurate estimation of the net emissions from reservoirs, the measurement of the emissions before and after the flooding of natural (aquatic) ecosystems is required as natural ecosystems cause emissions too (Mäkinen & Khan 2010). The amount and type of emitted greenhouse gases depend on the climatic conditions, the surface area, the depth of the water and its topography (Mäkinen & Khan 2010). The tropical reservoirs offer a range of factors that are favourable for the emission of large amounts of greenhouse gases: high temperatures, high levels of organic material, naturally productive carbon cycles and the combination of large surface areas with relatively shallow depth (Mäkinen & Khan 2010; Soumis et al. 2005). Alpine reservoirs on the other side are expected to have low emissions due to low water temperatures and a low input of nutrient[12].

Diem et al. (2008) have conducted the first measurements of greenhouse gas emissions of Swiss reservoirs. The measurements include several reservoirs across an altitude gradient in the Swiss Alps and calculations were done for the diffusive fluxes of CO_2, CH_4 and N_2O from the surface concentrations at different times of the year as well as losses at the turbine.

It is shown that only low land reservoirs (27 % of the total surface in Switzerland) are a source of N_2O while the subalpine and alpine reservoirs are in equilibrium with the atmospheric concentration. While there is no significant difference in the range of methane emissions due to diffusion between the different elevation levels, the altitude of the reservoirs seems to play a role regarding the emissions in the turbine. However this finding is strongly linked to the fact that in alpine power stations the head of the water is higher and therefore the gases have more time to outgas.

The results of measurements show an average emission of 1'030 mg CO_2/m^2d, 0.2 mg CH_4/m^2d and 72 µg N_2O/m^2d. With an average surface area of $7.21*10^5$ m^2 this results in specific greenhouse gas emissions of **1.36 g CO_2/kWh**, **$2.64*10^{-4}$ g CH_4/kWh** and **$2.56*10^{-5}$ g N_2O/kWh**. The latter considers only emissions from four reservoirs in the lowlands. Nearly 30% of the total area of the reservoirs of storage hydropower stations is located in the lowlands of Switzerland.

4.1.7 SF_6 emissions

SF_6 is applied in electric insulations, and switches. Considerable amounts of SF_6 emissions are only to be expected due to accidents and breakdowns (Vattenfall 2008). Vattenfall states that under normal conditions there is a continuous emission of **$3.40*10^{-7}$ g/kWh** (2008). The same amounts are included as material input to the operation of the storage hydropower station.

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[12] Eawag (2010): Stauseen als heimliche Klimasünder? Medienmitteilung vom 11. Oktober 2010

4.1.8 Operation of certified storage hydropower stations

The operation of certified storage hydropower stations is modelled similarly to the storage hydropower station described above.

Certified hydroelectric power only covers electricity produced with natural inflows. Hence, the amount of certified electricity is the net production of the hydropower plant (Bratrich & Truffer 2001). This is the total electricity produced minus the electricity consumed by the pumps. Consequently, the dataset reflecting the production of certified electricity from storage hydropower stations does not include an input of grid electricity.

4.2 Pumped storage power station

4.2.1 Land use, material input and emissions

Because it is difficult to separate the two types of hydropower stations, the pumped storage hydropower station and the storage hydropower station are modelled similarly. The infrastructure as well as the land use, material input and the emissions caused during the operation are the same. The only difference in the operation is the additional electricity consumption of the pumps used in pumped storage power stations.

4.2.2 Electricity use

The pumps of the Swiss pumped storage hydropower stations have an annual electricity consumption of 1657 GWh in 2010 (BFE 2011a, c). The average efficiency of the pumps is 0.8 (BFE 2011a), which results in 1326 GWh electricity produced per year in 2010. 1.25 kWh of electricity is needed to generate 1 kWh of electricity produced in basic water flow plants.

4.3 Run-of-river power station

As mentioned before, run-of-river hydropower stations are generally defined as hydropower stations without reservoirs. Among the run-of-river hydropower stations not included in the storage hydropower stations there are exceptions though.

The study of Del Sontro et al. (2010) has shown that reservoirs of run-of-river hydropower stations do not only lead to more land use but also to an increased amount of methane emissions. Consequently, two types of run-of-river hydropower stations are differentiated in the modelling of the operation phase: stations with and without a reservoir. While the land use, the water volume and the methane emissions are specific for these two types, the rest of inputs and emissions of the average run-of-river hydropower station modelled are the same.

For both types, the production of 1 kWh of electricity is modelled. The combination of the two types results in the modelled average run-of-river hydropower station. The run-of-river hydropower stations without reservoirs contribute 98 % to the total electricity production with run-of-river power stations.

4.3.1 Land use

It is difficult to determine the area of land used due to the construction and operation of run-of-river power stations without a reservoir. The first difficulty is to decide on the initial position: Run-of-river power stations are mostly constructed in stretches that are already obstructed due to flood protection and preservation of cultivated land. Is this the point of reference or is it the river before any modifications have taken place, close to nature? The latter leads to the question how the land transformations should be allocated to the power generation, the flood control and other modifications.

The second difficulty is to describe the impact of the land transformation. In Central Europe each river and its surrounding has its own characteristics, they are unique. It is often difficult to find the same or similar ecosystem a second time. If a considerable stretch is transformed due to flooding and disconnected from its natural cycles, it is lost.

Frischknecht et al. (1996) suggest taking the situation just before the construction of the power station (incl. earlier modifications). This gives not only a clear picture of the initial position but it also avoids the allocation problem. Further they suggest not examining the power stations individually but in the whole context. This means to consider the scarcity of the affected biotopes.

Generally the used area is quite small due to the geometry of the channel. The area itself is not a good measure though. Biologically wide and open river beds are more valuable than conventional ones, but they use more land.

The identification of land use due to run-of-river power stations faces various methodological difficulties. Frischknecht et al. (1996) have chosen a pragmatic approach which is followed for the run-of-river hydropower stations without reservoir as well. In a first step the area covered by the used stretch is determined by the product of the length (from the beginning of the slack flow to the dam) times the average width according to the map. The resulting area is not to be used as an absolute value but as an index. This index further includes that the run-of-river power station influences the biocoenosis in the affected stretches as well as the disturbance of the ground water flows as they are most often disconnected from the river due to the necessary sealing of the river. Frischknecht et al. (1996) determine a specific land transformation of $5.6*10^{-5}$ m^2/kWh for run-of-river hydropower stations without a reservoir. Large rivers tend to have a lower value while smaller rivers have a higher one. According to the approach used for the storage power stations 1 % is added to the land use for buildings and additional infrastructure of the power station ($1.72*10^3$ m^2/plant, resulting in a land transformation of $5.60*10^{-7}$ m^2/kWh). This leads to total values of $1.74*10^5$ m^2/plant or a land transformation of $5.66*10^{-5}$ m^2/kWh. The occupation of the land is **$4.52*10^{-3}$ m^2a** per kWh electricity produced with equals a total of $1.11*10^9$ m^2a over the lifespan of 80 years.

The land transformation due to the reservoir is $1.48*10^{-4}$ m^2/kWh produced in stations with a reservoir[13]. The total land transformation for power stations with a reservoir is therefore $2.04*10^{-4}$ m^2/kWh of water courses. The area covered by the infrastructure is the same as for the stations without a reservoir. The total land occupation amounts to **$1.63*10^{-2}$ m^2a** per kWh electricity produced which corresponds to $4.02*10^9$ m^2a over the lifespan of a run-of-river hydropower station.

According to Frischknecht et al. (1996), the initial state of the area before the construction of the run-of-river hydropower station is characterised as half "**shrub land, sclerophyllous**" and half "**pasture and meadow**". This accounts for the fact that most of the Swiss rivers have been modified due to flood protection and preservation of cultivated land. Because it is not allowed to fertilise land next to the river, it is assumed to be grown over with bushes and trees and, where this is not the case, it is used as pasture. The land is then transformed to "**water courses, artificial**" and "**industrial area, built up**".

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[13] Schweizerischer Wasserwirtschaftsverband, March 2011: http://www.swv.ch/de/statistik.cfm

4.3.2 Useful capacity of the reservoirs

The run-of-river power stations without reservoir are characterised by having no or only a small storage capacity. The specific capacity is therefor set to null.

The power stations with a reservoir have a storage capacity of $4.52*10^6$ m^3/plant; the storage capacity per kWh is **$1.03*10^{-3}$ m^3**.[14]

4.3.3 Water use and consumption

As it is already discussed in Section 4.1.3, the amount of turbined water correlates with the amount of produced electricity and the head. The ecological impact of the turbined water consists of the withdrawal of the water from its natural environment for a certain period of time.

The typical head of a run-of-river power station is 10 m (Frischknecht et al. 1996). This results in a specific amount of turbined water of **45 m^3/kWh** ($1.38*10^{11}$ m^3/plant) for the modelled run-of-river hydropower station (Frischknecht et al. 1996).

The water evaporated from reservoirs is estimated based on an average annual evaporation in Switzerland. It amounts to 484 mm (Spreafico & Weingartner 2005). In combination with the specific reservoir surface area of $1.48*10^{-4}$ m^2/kWh, this results in a specific evaporation of **5.71 kg/kWh**. It is listed as air emission “water, CH”.

4.3.4 Use of lubricating oil

A total loss of $9.33*10^{-4}$ g/kWh oil to the water and $9.49*10^{-4}$ g/kWh to the soil is specified over the whole life cycle of the hydropower station Wildegg-Brugg (Axpo 2008). Assuming a similar pattern of oil losses as for the power stations of Vattenfall (2008), 9 % of the total spill to the water and 4 % of the spill to the soil comes from the power station itself. Applied to the modelled run-of-river hydropower station this amounts in **$8.40*10^{-5}$ g/kWh** oil to the water and **$3.80*10^{-5}$ g/kWh** to the soil. Over the whole lifespan of the run-of-river hydropower station $2.58*10^2$ kg oil is spilled to the water and $1.17*10^2$ kg to the soil. The same amounts are included as material input to the operation of the power stations.

4.3.5 Greenhouse gas emissions

While the storage power stations store huge quantities of water in reservoirs, the run-of-river power stations do not require a large impoundment of water. Consequently there is no flooding of large areas of land necessary and it is assumed that run-of-river power stations without a reservoir do not emit greenhouse gases.

Del Sontro et al. (2010) have conducted measurements of the methane emissions in one of the reservoirs belonging to the sample of run-of-river hydropower stations under study, the lake of Wohlen. It is shown that the lake is a significant source of methane (156 mg CH_4/m^2d). It is assumed that all run-of-river power stations with a reservoir emit equal amounts of methane. This leads to an emission of **0.67 g CH_4/kWh** produced in run-of-river hydropower stations with reservoir ($2.07*10^6$ kg CH_4/plant).

4.4 Small hydropower stations

There are no data available for specific working material consumption and emissions during the operation of small hydropower stations.

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[14] Schweizerischer Wasserwirtschaftsverband, March 2011: http://www.swv.ch/de/statistik.cfm

4.5 Data quality

The operation of the storage hydropower stations is described well. Data describing the oil spill and the SF_6 emissions are derived from power stations not included in the sample under study. It is assumed though that the technology is the same and that the geographic differences are not significant. The greenhouse gas emissions are based on a study done on a significant share of the sample investigated. The geographic and technological correlation is good. The quantification of the land use and the volume of the reservoirs are based on current data. They do not only cover the same geography, the same technology and the same temporal aspects but the information is also available for the whole set of storage power stations under study. In general, the operation of the storage hydropower stations is described well and with low uncertainties.

The data of the operation of the run-of-river hydropower station on the other hand have more uncertainties. The factors for the land use of the stations without reservoir were adopted from earlier studies (Frischknecht et al. 1996) as no other data are available. This is also the case for the amount of turbined water and the volume of the water bodies. The methane emissions are based on one recent study conducted on one large run-of-river power station. This power station is part of the sample of this study but the emission factor might differ from the emissions of other run-of-river power stations. This leads to a relatively high uncertainty. In general, the operation of the run-of-river hydropower stations is described well. Further measurements of greenhouse gas emissions from reservoirs of run-of-river hydropower stations are needed (and currently on-going).

No information is available about the operation of small hydropower stations. This part of the life cycle is not well described.

4.6 Life Cycle inventories of the operation of hydropower plants

Tab. 4.1: Unit process raw data of electricity, hydropower, at reservoir power plant/CH and electricity, hydropower, net, at reservoir power plant/CH.

	Name	Location	Unit	electricity, hydropower, at reservoir power plant	electricity, hydropower, net, at reservoir power plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH	CH			
	InfrastructureProcess			0	0			
	Unit			kWh	kWh			
product	electricity, hydropower, at reservoir power plant	CH	kWh	1				
	electricity, hydropower, net, at reservoir power plant	CH	kWh		1			
technosphere	reservoir hydropower plant	CH	unit	3.35E-11	3.35E-11	1	3.05	(4,1,1,1,1,2,BU:3); Infrastructure of the storage power station producing the electricity
	sulphur hexafluoride, liquid, at plant	RER	kg	3.40E-10	3.40E-10	1	1.40	(4,5,1,5,1,5,BU:1.05); In electric insulation (e.g. switches); based on Vattenfall (2008)
	lubricating oil, at plant	RER	kg	3.24E-8	3.24E-8	1	1.40	(4,5,1,5,1,5,BU:1.05); Turbines; based on Vattenfall (2008)
	electricity, high voltage, at grid	CH	kWh	4.40E-2		1	1.12	(3,1,1,1,1,2,BU:1.05); Electricity consumption for the pumps (excl. pumped storage)
resource, land	Transformation, from unknown	-	m2	2.44E-5	2.44E-5	1	2.01	(3,1,1,1,1,1,BU:2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to water bodies, artificial	-	m2	2.41E-5	2.41E-5	1	2.01	(3,1,1,1,1,1,BU:2); Area covered by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to industrial area, built up	-	m2	2.41E-7	2.41E-7	1	2.05	(4,1,1,1,1,1,BU:2); Area covered by infrastructures other than held-back river; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, water bodies, artificial	-	m2a	3.62E-3	3.62E-3	1	1.52	(3,1,1,1,1,1,BU:1.5); Area occupied by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, industrial area, built up	-	m2a	3.62E-5	3.62E-5	1	1.56	(4,1,1,1,1,1,BU:1.5); Area occupied by the infrastructure; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
resource, in water	Volume occupied, reservoir	-	m3a	1.64E-1	1.64E-1	1	1.11	(3,1,1,1,1,1,BU:1.05); Volume occupied by the reservoir; based on Schweizerisches Talsperrenkomitee (2011)
	Water, turbine use, unspecified natural origin	-	m3	1.40E+0	1.40E+0	1	1.11	(3,1,1,1,1,1,BU:1.05); Amount of water turbined for the generation of electricity; based on BWW (1973)
	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	3.79E+0	1	1.11	(3,1,1,1,1,1,BU:1.05); Potential energy of the water
emission air, low population density	Dinitrogen monoxide	-	kg	2.56E-8	2.56E-8	1	1.58	(4,3,2,3,1,4,BU:1.5); Nitrous oxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Methane, biogenic	-	kg	2.64E-7	2.64E-7	1	1.57	(4,3,2,3,1,3,BU:1.5); Methane emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Carbon dioxide, land transformation	-	kg	1.36E-3	1.36E-3	1	1.48	(4,3,2,3,1,3,BU:1.4); Carbon dioxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Sulfur hexafluoride	-	kg	3.40E-10	3.40E-10	1	1.69	(4,5,1,5,1,5,BU:1.5); From electric insulations (e.g. switches); based on Vattenfall (2008)
	Heat, waste	-	MJ	1.58E-1	1.58E-1	1	1.12	(3,1,1,1,1,2,BU:1.05); Waste heat
emission air, unspecified	Water, CH	-	kg	1.75E+0	1.75E+0	1	1.89	(4,3,3,2,4,5,BU:1.5); Water evaporated from reservoir; calculated based on Spreafico & Weingartner (2005)
emission water, river	Oils, unspecified	-	kg	2.27E-8	2.27E-8	1	1.69	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	9.76E-9	9.76E-9	1	1.69	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)

Tab. 4.2: Unit process raw data of electricity, hydropower, at pumped storage power plant/CH.

	Name	Location	Unit	electricity, hydropower, at pumped storage power plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, hydropower, at pumped storage power plant	CH	kWh	1			
technosphere	lubricating oil, at plant	RER	kg	3.24E-8	1	1.40	(4,5,1,5,1,5,BU:1.05); Turbines; based on Vattenfall (2008)
	reservoir hydropower plant	CH	unit	3.35E-11	1	3.05	(4,1,1,1,1,2,BU:3); Infrastructure of the storage power station producing the electricity
	sulphur hexafluoride, liquid, at plant	RER	kg	3.40E-10	1	1.40	(4,5,1,5,1,5,BU:1.05); In electric insulation (e.g. switches); based on Vattenfall (2008)
	electricity, high voltage, at grid	CH	kWh	1.25E+0	1	1.22	(4,1,1,1,1,3,BU:1.05); For the pumping of the water; bfe (2010)
resource, land	Transformation, from unknown	-	m2	2.44E-5	1	2.01	(3,1,1,1,1,1,BU:2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to water bodies, artificial	-	m2	2.41E-5	1	2.01	(3,1,1,1,1,1,BU:2); Area covered by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to industrial area, built up	-	m2	2.41E-7	1	2.05	(4,1,1,1,1,1,BU:2); Area covered by infrastructures other than held-back river; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, water bodies, artificial	-	m2a	3.62E-3	1	1.52	(3,1,1,1,1,1,BU:1.5); Area occupied by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, industrial area, built up	-	m2a	3.62E-5	1	1.56	(4,1,1,1,1,1,BU:1.5); Area occupied by the infrastructure; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
resource, in water	Volume occupied, reservoir	-	m3a	1.64E-1	1	1.11	(3,1,1,1,1,1,BU:1.05); Volume occupied by the reservoir; based on Schweizerisches Talsperrenkomitee (2011)
	Water, turbine use, unspecified natural origin	-	m3	1.40E+0	1	1.11	(3,1,1,1,1,1,BU:1.05); Amount of water turbined for the generation of electricity; based on BWW (1973)
emission air, low population density	Dinitrogen monoxide	-	kg	2.56E-8	1	1.58	(4,3,2,3,1,4,BU:1.5); Nitrous oxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Methane, biogenic	-	kg	2.64E-7	1	1.57	(4,3,2,3,1,3,BU:1.5); Methane emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Carbon dioxide, land transformation	-	kg	1.36E-3	1	1.48	(4,3,2,3,1,3,BU:1.4); Carbon dioxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Sulfur hexafluoride	-	kg	3.40E-10	1	1.69	(4,5,1,5,1,5,BU:1.5); From electric insulations (e.g. switches); based on Vattenfall (2008)
emission air, unspecified	Water, CH	-	kg	1.75E+0	1	1.89	(4,3,3,2,4,5,BU:1.5); Water evaporated from reservoir; calculated based on Spreafico & Weingartner (2005)
emission water, river	Oils, unspecified	-	kg	2.27E-8	1	1.69	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	9.76E-9	1	1.69	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission air, low population density	Heat, waste	-	MJ	9.00E-1	1	1.22	(4,1,1,1,1,3,BU:1.05); Heat emissions

Tab. 4.3: Unit process raw data of electricity, hydropower, at run-of-river power plant with reservoir/CH, electricity, at run-of-river power station without reservoir/CH and electricity, hydropower, at run-of-river power plant, mix/CH.

	Name	Location	Unit	electricity, hydropower, at run-of-river power plant with reservoir	electricity, hydropower, at run-of-river power plant without reservoir	electricity, hydropower, at run-of-river power plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH	CH	CH			
	InfrastructureProcess			0	0	0			
	Unit			kWh	kWh	kWh			
product	electricity, hydropower, at run-of-river power plant with reservoir	CH	kWh	1					
	electricity, hydropower, at run-of-river power plant without reservoir	CH	kWh		1				
	electricity, hydropower, at run-of-river power plant	CH	kWh			1			
technosphere	electricity, hydropower, at run-of-river power plant with reservoir	CH	kWh			1.98E-2	1	1.27	(4,3,3,1,1,4,BU:1.05); Proportion of hydropower from run-of-river hydropower stations with reservoir
	electricity, hydropower, at run-of-river power plant without reservoir	CH	kWh			9.80E-1	1	1.27	(4,3,3,1,1,4,BU:1.05); Proportion of hydropower from run-of-river hydropower stations without reservoir
	run-of-river hydropower plant	CH	unit	3.25E-10	3.25E-10		1	3.07	(4,3,3,1,1,4,BU:3); Infrastructure of the run-of-river power station producing the electricity
	lubricating oil, at plant	RER	kg	1.22E-7	1.22E-7		1	1.48	(4,5,3,5,3,5,BU:1.05); In turbines; based on Axpo (2008) and Vattenfall (2008)
resource, land	Transformation, to industrial area, built up	-	m2	5.60E-7	5.60E-7		1	2.11	(4,3,3,1,1,5,BU:2); Area covered by infrastructures, not the river; based on Frischknecht et al. (1996)
	Transformation, from shrub land, sclerophyllous	-	m2	1.02E-4	2.83E-5		1	2.11	(4,3,3,1,1,5,BU:2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996)
	Transformation, from pasture and meadow	-	m2	1.02E-4	2.83E-5		1	1.40	(4,3,3,1,1,5,BU:1.2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996)
	Transformation, to water courses, artificial	-	m2	2.04E-4	5.60E-5		1	2.11	(4,3,3,1,1,5,BU:2); Area covered by the river; recalculated based on Frischknecht et al. (1996)
	Occupation, water courses, artificial	-	m2a	1.63E-2	4.48E-3		1	1.64	(4,3,3,1,1,5,BU:1.5); Area occupied due to the run-of-river hydropower station; recalculated based on Frischknecht et al. (1996)
	Occupation, industrial area, built up	-	m2a	4.48E-5	4.48E-5		1	1.64	(4,3,3,1,1,5,BU:1.5); Area occupied due to the run-of-river hydropower station; recalculated based on Frischknecht et al. (1996)
resource, in water	Volume occupied, reservoir	-	m3a	8.24E-2			1	1.33	(4,3,3,1,1,5,BU:1.05); Volume occupied due to the run-of-river hydropower station; recalculated based on Frischknecht et al. (1996)
	Water, turbine use, unspecified natural origin	-	m3	4.50E+1	4.50E+1		1	1.33	(4,3,3,1,1,5,BU:1.05); Amount of water turbined for the generation of electricity; based on Frischknecht et al. (1996)
	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	3.79E+0		1	1.11	(3,1,1,1,1,1,BU:1.05); Potential energy of the water
emission air, unspecified	Water, CH	-	kg	5.71E+0			1	1.89	(4,3,3,2,4,5,BU:1.5); Water evaporated from reservoir; calculated based on Spreafico & Weingartner (2005)
emission water, river	Oils, unspecified	-	kg	8.40E-8	8.40E-8		1	1.75	(4,5,3,5,3,5,BU:1.5); From turbines; based on Axpo (2008) and Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	3.80E-8	3.80E-8		1	1.75	(4,5,3,5,3,5,BU:1.5); From turbines; based on Axpo (2008) and Vattenfall (2008)
emission air, low population density	Methane, biogenic	-	kg	6.72E-4			1	1.64	(4,3,3,3,1,5,BU:1.5); Methane emissions due to the held-back river; DelSontro et al. (2010)

Tab. 4.4: Unit process raw data of electricity, hydropower, at small hydropower plant, in waterworks infrastructure/CH and electricity, hydropower, at small hydropower plant/CH.

	Name	Location	Unit	electricity, hydropower, at small hydropower plant, in waterworks infrastructure	electricity, hydropower, at small hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			CH	CH			
	InfrastructureProcess			0	0			
	Unit			kWh	kWh			
product	electricity, hydropower, at small hydropower plant, in waterworks infrastructure	CH	kWh	1	0			
	electricity, hydropower, at small hydropower plant	CH	kWh	0	1			
technosphere	small hydropower plant, in waterworks infrastructure	CH	unit	1.23E-8		1	3.11	(4,3,3,3,3,3,BU:3); literature
	small hydropower plant	CH	unit		1.29E-8	1	3.11	(4,3,3,3,3,3,BU:3); literature
resource, in water	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	3.79E+0	1	1.33	(4,3,3,3,3,3,BU:1.05); Potenzielle Energie Wasser; literature

5 Deconstruction of the hydropower stations

There is no long-term experience with hydropower stations at the end of their lifespan and consequently nothing is known about the handling of such hydropower stations. It is assumed, that the dams will not be deconstructed but they will be abandoned (Frischknecht et al. 1996). Furthermore it seems probable that the other parts of storage power stations as well as of run-of-river power stations are replaced by new plants at the end of their lifetime (Frischknecht et al. 1996; Vattenfall 2008). The old parts will be deconstructed to give space to new ones, while the dams are continuously maintained. The deconstructed material needs to be transported and handled accurately. For the new power station no excavation is needed anymore and other energy intense parts of the construction might fall away too. The exact allocation between the two generations of power stations is an open question.

With the replacement of the hydropower station, there is neither a re-cultivation nor a land transformation to be considered. The complete abandoning of the dams on the other hand would lead to a siltation of the lake with a gradual re-cultivation. However, there is no certainty that the same vegetation, typical for this habitat, establishes again. This does not per se mean a decline in the quality of the fauna as the arising areas might offer niches for rare species.

In this study it is assumed that the hydropower stations are replaced. This applies not only to the storage and run-of-river hydropower stations, but also for both types of small hydropower stations. The disposal activities are included in the infrastructure datasets (construction of hydroelectric power stations, see Chapter 3).

5.1 Storage power stations

As described above, it is assumed that the dam is not deconstructed at the end of its lifespan. Therefore the handling of the non-reinforced concrete is modelled as “to final disposal”. The amount of non-reinforced concrete is defined as follows: It is assumed that the total amount of reinforcing steel is used in the product “reinforced concrete”. One kilo of reinforced concrete consists of 0.03 kg reinforcing steel and 0.97 kg concrete (Doka 2009). With an amount of $1.74*10^6$ kg reinforcing steel a total of $5.79*10^7$ kg reinforced concrete can be produced. The remaining $9.36*10^8$ kg of concrete which is not used in the product “reinforced concrete” is treated as non-reinforced concrete. After 150 years, the reinforced concrete goes to recycling, the non-reinforced concrete goes to the final disposal, as already mentioned.

For the end-of-life treatment of other metals a recycling rate of 100% is assumed.

5.2 Run-of-river power stations

The treatment of the concrete (reinforced and non-reinforced) is modelled as described above: the reinforced concrete is recycled, the non-reinforced one goes “to final disposal”. At the end of the lifetime of the run-of-river hydropower stations there is a total of $1.58*10^7$ kg reinforced concrete (to recycling) and $4.08*10^7$ kg non-reinforced concrete (to final disposal).

For the end-of-life treatment of other metals than the reinforcing steel a recycling rate of 100 % is assumed.

5.3 Small hydropower stations

5.3.1 Small hydropower plant in waterworks infrastructure

It is assumed that the total amount of reinforcing steel ($2.12*10^3$ kg) is used to reinforce concrete. The resulting $7.05*10^4$ kg reinforced concrete is recycled at the end of its lifetime. The remaining $5.31*10^4$ kg of concrete (non-reinforced concrete) is assumed to remain on-site, which is modelled as “to final disposal”.

The gravel is left within the remaining infrastructure of the dams and in the ditch of the pipes. Therefore it goes “to final disposal” too.

The plastics (PE and PVC) and the wood as well as glass and the other non-metals are assumed to be incinerated in a municipal waste incineration plant.

For the remaining metals a recycling rate of 100 % is assumed.

5.3.2 Standalone small hydropower plant

For this type of hydropower plants the ratio between the concrete and the reinforcing steel is reversed. A total amount of $1.43*10^6$ kg reinforced concrete is used ($1.39*10^6$ kg concrete plus $4.29*10^4$ kg reinforcing steel). Both, the reinforced concrete and the remaining $7.05*10^3$ kg of reinforcing steel are recycled at the end of the use phase.

The gravel is left on-site, which is modelled as “to final disposal”. All the non-metallic materials (plastics, wood, glass etc.) are assumed to be incinerated in a municipal waste incineration plant. For the remaining metals a recycling rate of 100 % is assumed.

5.4 Data quality

As there is no experience with the handling of hydropower stations at the end of use, it is on the one hand difficult to model this phase, but it is also difficult to evaluate the data. The quantities of the materials to be deposited and of the corresponding uncertainties are based on the data of the construction phase. Predictions of the treatment of the materials leads to relatively high uncertainties, as it is not possible to know yet how the power stations will be handled at the end of their useful life.

6 Life Cycle Inventory data of hydropower stations in other countries

6.1 European hydropower stations

6.1.1 Storage and pumped storage hydropower stations

It is assumed that there is no significant difference between the infrastructure of storage power stations in Switzerland and the alpine regions of Europe. Therefore the same data are used. Where available, the processes are adapted to European processes (RER). As the data in the inventory are representative for Switzerland, storage power stations that lay outside of the alpine area get an increased uncertainty by factor 1.25 (Bolliger & Bauer 2007). This is due to other geologic and hydrologic characteristics. Furthermore, the technology might vary.

The operation of the storage hydropower stations in Europe is based on the data set of the Swiss storage power stations too. The consumption of lubricating oil and SF_6 as well as their emissions remain the same. The uncertainty is adapted according to the pattern described above. In Subchapter 6.3 the unit process raw data of the electricity production in Europe (RER) is presented.

The electricity mix for the operation of the pumped storage hydropower stations in other countries is adapted. The following countries are considered: Austria, Bosnia and Herzegovina, Belgium, Serbia and Montenegro, Czech Republic, Germany, Spain, France, the United Kingdom, Greece, Croatia, Ireland, Italy, Luxemburg, Macedonia, Norway, Poland, Portugal, Sweden, Slovenia and Slovakia as well as Australia, Canada, India, Japan, Korea, Malaysia, South Africa and the United States. In Subchapter 6.3 only the unit process raw data of the electricity production in Europe (RER) is presented as an example. The datasets of the operation of pumped storage hydropower station in other countries are not shown.

It is assumed that the geographic and climatic conditions are the same for storage power stations operating in the alpine regions of Europe. Therefore the land transformation and the amount of water turbined and evaporated remains the same for these power stations. This applies for the greenhouse gas emissions too as it can be further assumed that the climatic conditions do not vary much within the alpine area. In case of the water evaporated, the elementary flow of the air emissions is adapted to the respective regional reference.

The topographic conditions are different outside the alpine regions though. While the reservoirs in the Alps are most often located in steep narrow valleys, the landscape in the non-alpine regions is flatter. This leads to more shallow reservoirs with a larger area covered. To take this into account, their land use is assumed to be ten times higher than for the alpine reservoirs (Bolliger & Bauer 2007). The volume of the water bodies is multiplied with the same factor as well as the amount of turbined water. The water evaporated from the reservoirs is calculated from the global average of 25 kg/kWh specified by Pfister et al. (2011). The elementary flow is adapted according to the respective regional reference.

As the N_2O emission factors apply for lowland reservoirs only, they are also valid for non-alpine regions. The area is larger though, which leads to higher N_2O emissions ($9.51*10^{-4}$ g/kWh). For the other greenhouse gas emissions other factors are needed. In literature, an average emission factor of about 820 mg CO_2/m^2d and 3.6 mg CH_4/m^2d is given for temperate regions (Soumis et al. 2005). The larger area covered leads to CO_2 emissions of 10.8 g/kWh and specific CH_4 emissions of $4.8*10^{-2}$ g/kWh.

6.1.2 Run-of-river

The construction of the run-of-river stations in Europe is assumed to be the same as in Switzerland. As far as possible the processes are adapted to European processes (RER). The factors of the methane emissions from run-of-river hydropower stations with reservoirs are the same as there are no significant geographic or climatic differences.

The water evaporated from the reservoirs is calculated from the global average of 25 kg/kWh specified by Pfister et al. (2011). The elementary flow is adapted according to the respective regional reference.

The uncertainties are increased by a factor of 1.2 to account for differences. For the same reason the uncertainty of the data set describing the operation of the European hydropower stations is increased too. There are no further differences to the Swiss data sets.

6.1.3 Small hydropower

The construction of the small hydropower stations is modelled in the same way as the Swiss power stations. European processes (RER) are used where they are available.

The differences between the two regions are considered by increasing the uncertainties by a factor of 1.2. This is done for the infrastructure as well as for the operation of the small hydropower stations. There are no further differences to the Swiss data sets.

6.2 Brazil

An average Brazilian storage hydropower is modelled based on information from the Itaipu hydropower station (Binacional 2000) and completed with data from non-alpine storage hydropower stations. The dataset describes this specific hydropower station and not an average Brazilian station.

The construction consumes a total of $3.90*10^6$ m^3/plant concrete (Binacional 2000). The weight of the turbines and generators is $7.00*10^6$ kg (Binacional 2000). In a first approach it is assumed that the turbines and generators consist primarily of steel. Due to missing data, the amount of reinforcing steel and low-alloyed steel for the construction of the stations is modelled according to the proportions of the storage power stations in Europe, including a lifespan of 150 years for reinforcing steel and 80 years for the other types: $1.26*10^7$ kg/plant reinforcing steel, $5.51*10^7$ kg/plant steel low-alloyed and $1.31*10^7$ kg/plant of chromium steel. The consumption of all the other materials as well as the transports during the construction are based on the specific values of the European storage hydropower stations and adjusted to the production figures of the Itaipu hydropower station too. The particle emissions are based on the emission factors of general construction sites in Switzerland (BUWAL 2001, 2003). The area of the construction site is assumed to be twice the area of the dam and other infrastructures (1 % of the area of the reservoir), see also Section 4.1.1. The resulting unit process raw data of an average storage hydropower station in Brazil is shown in Tab. 6.9.

The specific land use and the volume of the reservoir is derived from the Itaipu hydropower station (Binacional 2000), whereas the use and emission of oil and SF_6 as well as the electricity consumption are based on the specific data of the electricity production in non-alpine hydropower stations in Europe. The area covered by the hydropower station is $1.35*10^9$ m^2. The transformation is modelled as “from tropical rain forest” to “water bodies, artificial” and “industrial area, built up”. The latter is an additional 1 % of the area covered by the reservoir.

The water evaporated from the reservoirs is calculated from the global average of 25 kg/kWh specified by Pfister et al. (2011). The elementary flow is adapted according to the respective regional reference.

The greenhouse gas emission factors are a widely discussed matter. Many publications on this subject are available (dos Santos et al. 2006; Lima 2005; Rosa et al. 2003; Rosa et al. 2004 and more). Nevertheless no official factors are available yet. The emission factors vary widely from source to source (Tab. 6.1).

Tab. 6.1: Greenhouse gas emissions of Brazilian storage hydropower stations. The values are derived from different literature sources.

	Reservoir	**CO_2 (mg/m^{2}d)**	**CH_4 (mg/m^{2}d)**
Diem et al. 2008	Tucurui	-	13.82
	Samuel	-	71.19
St.Louis et al. 2009	Tropical reservoirs	3'500	300
Rosa et al. 2003	Tucurui	8'088 5'350	183.6 209.2
	Samuel	10'433 6'516	24.4 14.6
dos Santos et al. 2006	Miranda	4'980	262.4
	Tres marias	-142	328.2
	Barra	6'434	19.2
	Bonita	4'789	9.9
	Segredo	9'837	29.99
	Xingo	8'087	183.6
	Tucurui	10'433	205.4
	Itaipu	1'205	12.9
	Serra da Mesa	1'316	121

For this study an average of 7.6 g CO_2/m^{2}d and 86 mg CH_4/m^{2}d is implemented (Lima 2005; Rosa et al. 2003). This leads to emissions of 31 g CO_2/kWh and 0.56 g CH_4/kWh. The variation in literature and the many open questions regarding the origin of the gases and the development over time leads to high uncertainties. Therefore the uncertainty factor of these emission factors is set to 2 for the CO_2 emissions and 4 for the CH_4 emissions.

This data set is generally afflicted with high uncertainties as the raw data are based on one single Brazilian storage hydropower station and European data, which are adopted without further adaptions to the Brazilian conditions.

6.3 Life Cycle inventories of the operation of hydropower stations in other countries

The operation of the hydropower stations in other countries is described in the Subchapters 6.1 and 6.2.

Tab. 6.2: Unit process raw data of reservoir hydropower plant, alpine/RER and reservoir hydropower plant, non-alpine/RER.

	Name	Location	Unit	reservoir hydropower plant, alpine region	StandardDeviation95%	reservoir hydropower plant, non alpine regions	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER		RER			
	InfrastructureProcess			1		1			
	Unit			unit		unit			
product	reservoir hydropower plant, alpine region	RER	unit	1					
	reservoir hydropower plant, non alpine regions	RER	unit			1			
technosphere	chromium steel 18/8, at plant	RER	kg	1.82E+6	1.24	1.82E+6	1	1.55	(4,3,1,3,1,4,BU:1.05); Turbines and generators; recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	diesel, burned in building machine	GLO	MJ	5.97E+7	1.24	5.97E+7	1	1.55	(4,3,1,3,1,4,BU:1.05); Fuel for construction machines; based on Frischknecht et al. (1996)
	explosives, tovex, at plant	CH	kg	5.95E+5	1.24	5.95E+5	1	1.55	(4,3,1,3,1,4,BU:1.05); Tunnels and galleries; recalculated based on Béguin et al. 1963, Bertschinger 1959, Blenio Kraftwerke 1968, Condrau 1962, KVR 1963; 1968, Töndury 1956; 1964, Weber et al. 1965 and other sources.
	gravel, round, at mine	CH	kg	8.89E+8	1.24	8.89E+8	1	1.55	(3,5,1,3,1,2,BU:1.05); Concrete for dams, buildings and other infrastructure; recalculated based on Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), DesMeules (1961), Gicot (1956), KVR (1968), Link(1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961; 1971), Stucky (1962), Töndury (1956; 1964), Walther & Fetz (1963; 1971), Weber et al. (1965; 1970), Zingg(1961).
	cement, unspecified, at plant	CH	kg	1.02E+8	1.24	1.02E+8	1	1.55	(3,5,1,3,1,2,BU:1.05); Concrete for dams, buildings and other infrastructure; recalculated based on Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), DesMeules (1961), Gicot (1956), KVR (1968), Link(1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961; 1971), Stucky (1962), Töndury (1956; 1964), Walther & Fetz (1963; 1971), Weber et al. (1965; 1970), Zingg(1961).
	reinforcing steel, at plant	RER	kg	1.74E+6	1.24	1.74E+6	1	1.55	(4,3,1,3,1,4,BU:1.05); Buildings and other infrastructure; recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	steel, low-alloyed, at plant	RER	kg	4.07E+6	1.24	4.07E+6	1	1.55	(4,3,1,3,1,4,BU:1.05); Tubes and pipes; recalculated based on recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	copper, at regional storage	RER	kg	2.96E+5	1.34	2.96E+5	1	1.68	(3,5,1,5,1,5,BU:1.05); Electric cables; Vattenfall (2008)
	tap water, at user	RER	kg	5.65E+7	1.24	5.65E+7	1	1.55	(3,5,1,3,1,2,BU:1.05); Concrete for dams, buildings and other infrastructure; recalculated based on Aegina (1965), Bertschinger (1959), Biedermann et al. (1985), DesMeules (1961), Gicot (1956), KVR (1968), Link(1970), Meyer (1960), Morf (1962), Salanfe (1951), Schnitter (1961; 1971), Stucky (1962), Töndury (1956; 1964), Walther & Fetz (1963; 1971), Weber et al. (1965; 1970), Zingg(1961).
	electricity, medium voltage, production ENTSO, at grid	ENTSO	kWh	2.73E+7	1.24	2.73E+7	1	1.55	(4,3,1,3,1,4,BU:1.05); Electricity supply for the construction; recalculated based on Bertschinger (1959), Blenio Kraftwerke (1968), KVR (1968), Töndury (1964), Walther und Fetz (1963), Weber et al. (1965), BFE (1992) and other sources.
	disposal, building, reinforced concrete, to recycling	CH	kg	5.79E+7	1.24	5.79E+7	1	1.55	(4,3,1,3,1,4,BU:1.05); Recycling of reinforced infrastructure; based on Frischknecht (1996), assumed recycling rate: 100%
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	9.36E+8	1.24	9.36E+8	1	1.55	(4,3,1,3,1,4,BU:1.05); Non-inforced infrastructure left on-site at the end of the use phase of the power station (especially the dams, tunnels, galleries); based on Frischknecht et al. (1996)
	disposal, building, reinforcement steel, to recycling	CH	kg	5.88E+6	1.24	5.88E+6	1	1.55	(4,3,1,3,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; assumed recycling rate: 100%
	transport, lorry >16t, fleet average	RER	tkm	4.78E+6	2.09	4.78E+6	1	2.62	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Bertschinger (1959)
	transport, freight, rail	RER	tkm	2.61E+7	2.09	2.61E+7	1	2.62	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Bertschinger (1959)
emission air, low population density	Heat, waste	-	MJ	9.82E+7	1.24	9.82E+7	1	1.55	(4,3,1,3,1,4,BU:1.05); From electricity
	Particulates, < 2.5 um	-	kg	1.03E+2	3.61	1.03E+2	1	4.51	(4,5,5,5,4,5,BU:3); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 10 um	-	kg	2.06E+3	2.17	2.06E+3	1	2.72	(4,5,5,5,4,5,BU:1.5); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 2.5 um, and < 10um	-	kg	5.84E+2	2.61	5.84E+2	1	3.26	(4,5,5,5,4,5,BU:2); Particle emissions during the construction; based on BUWAL (2001, 2003)

Tab. 6.3: Unit process raw data of electricity, hydropower, at reservoir power plant, alpine region/RER and electricity, hydropower, at reservoir power plant, non-alpine region/RER.

	Name	Location	Unit	electricity, hydropower, at reservoir power plant, alpine region	StandardDeviation95%	electricity, hydropower, at reservoir power plant, non alpine regions	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER		RER			
	InfrastructureProcess			0		0			
	Unit			kWh		kWh			
product	electricity, hydropower, at reservoir power plant, alpine region	RER	kWh	1					
	electricity, hydropower, at reservoir power plant, non alpine regions	RER	kWh			1			
technosphere	reservoir hydropower plant, alpine region	RER	unit	3.35E-11	3.78		1	4.72	(4,5,1,5,1,5,BU:3); Infrastructure of the storage power station producing the electricity
	reservoir hydropower plant, non alpine regions	RER	unit		3.78	3.35E-11	1	4.72	(4,5,1,5,1,5,BU:3); Infrastructure of the storage power station producing the electricity
	sulphur hexafluoride, liquid, at plant	RER	kg	3.40E-10	1.67	3.40E-10	1	2.09	(4,5,1,5,1,5,BU:1.05); In electric insulation (e.g. switches); based on Vattenfall (2008)
	lubricating oil, at plant	RER	kg	3.24E-8	1.67	3.24E-8	1	2.09	(4,5,1,5,1,5,BU:1.05); Turbines; based on Vattenfall (2008)
resource, land	Transformation, from unknown	-	m2	2.44E-5	2.42	2.44E-4	1	3.02	(3,1,1,1,1,1,BU:2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to water bodies, artificial	-	m2	2.41E-5	2.42	2.41E-4	1	3.02	(3,1,1,1,1,1,BU:2); Area covered by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to industrial area, built up	-	m2	2.41E-7	2.46	2.41E-6	1	3.07	(4,1,1,1,1,1,BU:2); Area covered by infrastructures other than held-back river; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, water bodies, artificial	-	m2a	3.62E-3	1.82	3.62E-2	1	2.28	(3,1,1,1,1,1,BU:1.5); Area occupied by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, industrial area, built up	-	m2a	3.62E-5	1.87	3.62E-4	1	2.34	(4,1,1,1,1,1,BU:1.5); Area occupied by the infrastructure; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
resource, in water	Volume occupied, reservoir	-	m3a	1.64E-1	1.34	1.64E+0	1	1.67	(3,1,1,1,1,1,BU:1.05); Volume occupied by the reservoir; based on Schweizerisches Talsperrenkomitee (2011)
	Water, turbine use, unspecified natural origin	-	m3	1.40E+0	1.34	1.40E+1	1	1.67	(3,1,1,1,1,1,BU:1.05); Amount of water turbined for the generation of electricity; based on BWW (1973)
	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	1.34	3.79E+0	1	1.67	(3,1,1,1,1,1,BU:1.05); Potential energy of the water
emission air, low population density	Dinitrogen monoxide	-	kg	2.56E-8	1.90	9.51E-7	1	2.37	(4,3,2,3,1,4,BU:1.5); Nitrous oxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Methane, biogenic	-	kg	2.64E-7	1.88	4.78E-5	1	2.36	(4,3,2,3,1,3,BU:1.5); Methane emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Carbon dioxide, land transformation	-	kg	1.36E-3	1.77	1.08E-2	1	2.22	(4,3,2,3,1,3,BU:1.4); Carbon dioxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Sulfur hexafluoride	-	kg	3.40E-10	2.02	3.40E-10	1	2.53	(4,5,1,5,1,5,BU:1.5); From electric insulations (e.g. switches); based on Vattenfall (2008)
	Heat, waste	-	MJ	1.58E-1	1.34		1	1.67	(3,1,1,1,1,2,BU:1.05); Waste heat
emission air, unspecified	Water, OECD	-	kg	1.75E+0	2.27	2.50E+1	1	2.84	(4,3,3,2,4,5,BU:1.5); Water evaporated from reservoir; calculated based on Pfister et al. (2011)
emission water, river	Oils, unspecified	-	kg	2.27E-8	2.02	2.27E-8	1	2.53	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	9.76E-9	2.02	9.76E-9	1	2.53	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)

Tab. 6.4: Unit process raw data of electricity, hydropower, at pumped storage power plant/RER.

	Name	Location	Unit	electricity, hydropower, at pumped storage power plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, hydropower, at pumped storage power plant	RER	kWh	1			
technosphere	lubricating oil, at plant	RER	kg	3.24E-8	1	1.67	(4,5,1,5,1,5,BU:1.05); Turbines; based on Vattenfall (2008)
	reservoir hydropower plant, alpine region	RER	unit	3.35E-11	1	3.78	(4,5,1,5,1,5,BU:3); Infrastructure of the storage power station producing the electricity
	sulphur hexafluoride, liquid, at plant	RER	kg	3.40E-10	1	1.67	(4,5,1,5,1,5,BU:1.05); In electric insulation (e.g. switches); based on Vattenfall (2008)
	electricity, high voltage, production ENTSO, at grid	ENTSO	kWh	1.25E+0	1	1.97	(5,5,2,5,1,5,BU:1.05); For the pumping of the water; bfe (2010)
resource, land	Transformation, from unknown	-	m2	2.44E-5	1	2.42	(3,1,1,1,1,1,BU:2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to water bodies, artificial	-	m2	2.41E-5	1	2.42	(3,1,1,1,1,1,BU:2); Area covered by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Transformation, to industrial area, built up	-	m2	2.41E-7	1	2.46	(4,1,1,1,1,1,BU:2); Area covered by infrastructures other than held-back river; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, water bodies, artificial	-	m2a	3.62E-3	1	1.82	(3,1,1,1,1,1,BU:1.5); Area occupied by the reservoir; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
	Occupation, industrial area, built up	-	m2a	3.62E-5	1	1.87	(4,1,1,1,1,1,BU:1.5); Area occupied by the infrastructure; recalculated based on Frischknecht et al. (1996) and Schweizerisches Talsperrenkomitee (2011)
resource, in water	Volume occupied, reservoir	-	m3a	1.64E-1	1	1.34	(3,1,1,1,1,1,BU:1.05); Volume occupied by the reservoir; based on Schweizerisches Talsperrenkomitee (2011)
	Water, turbine use, unspecified natural origin	-	m3	1.40E+0	1	1.34	(3,1,1,1,1,1,BU:1.05); Amount of water turbined for the generation of electricity; based on BWW (1973)
emission air, low population density	Dinitrogen monoxide	-	kg	2.56E-8	1	1.90	(4,3,2,3,1,4,BU:1.5); Nitrous oxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Methane, biogenic	-	kg	2.64E-7	1	1.88	(4,3,2,3,1,3,BU:1.5); Methane emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Carbon dioxide, land transformation	-	kg	1.36E-3	1	1.77	(4,3,2,3,1,3,BU:1.4); Carbon dioxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Sulfur hexafluoride	-	kg	3.40E-10	1	2.02	(4,5,1,5,1,5,BU:1.5); From electric insulations (e.g. switches); based on Vattenfall (2008)
emission air, unspecified	Water, OECD	-	kg	1.75E+0	1	2.27	(4,3,3,2,4,5,BU:1.5); Water evaporated from reservoir; calculated based on Spreafico & Weingartner (2005)
emission water, river	Oils, unspecified	-	kg	2.27E-8	1	2.02	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	9.76E-9	1	2.02	(4,5,1,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission air, low population density	Heat, waste	-	MJ	9.00E-1	1	1.46	(4,1,1,1,1,3,BU:1.05); Heat emissions

Tab. 6.5: Unit process raw data of run-of-river hydropower plant/RER.

	Name	Location	Unit	run-of-river hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER			
	InfrastructureProcess			1			
	Unit			unit			
product	run-of-river hydropower plant	RER	unit	1			
technosphere	chromium steel 18/8, at plant	RER	kg	9.23E+4	1	1.55	(4,3,3,5,1,4,BU:1.05); Turbines and generators; based on Frischknecht et al. (1996) and Bauer et al. (2007)
	diesel, burned in building machine	GLO	MJ	1.45E+7	1	1.70	(4,5,3,5,1,5,BU:1.05); Fuel for construction machines; recalculated based on Frischknecht et al. (1996)
	explosives, tovex, at plant	CH	kg	1.94E+3	1	1.70	(4,5,3,5,1,5,BU:1.05); Tunnels and galleries; based on Bauer et al. (2007)
	gravel, round, at mine	CH	kg	5.03E+7	1	1.55	(4,3,3,5,1,4,BU:1.05); Concrete for buildings and other infrastructure; recalculated based on Frischknecht et al. (1996)
	cement, unspecified, at plant	CH	kg	5.78E+6	1	1.55	(4,3,3,5,1,4,BU:1.05); Concrete for buildings and other infrastructure; recalculated based on Frischknecht et al. (19969
	reinforcing steel, at plant	RER	kg	4.73E+5	1	1.55	(4,3,3,5,1,4,BU:1.05); Buildings and other infrastructure; based on Frischknecht et al. (1996) and Bauer et al. (2007)
	steel, low-alloyed, at plant	RER	kg	1.27E+6	1	1.55	(4,3,3,5,1,4,BU:1.05); Tubes and pipes; based on Frischknecht et al. (1996) and Bauer et al. (2007)
	copper, at regional storage	RER	kg	3.05E+4	1	1.83	(4,5,4,5,3,5,BU:1.05); Electric cables; calculated based on Axpo (2008)
	tap water, at user	RER	kg	3.19E+6	1	1.55	(4,3,3,5,1,4,BU:1.05); Concrete for buildings and other infrastructure; recalculated based on Frischknecht et al. (1996)
	electricity, medium voltage, domestic production, at grid	ENTSO	kWh	1.54E+6	1	1.70	(4,5,3,5,1,5,BU:1.05); Electricity supply for the construction; recalculated based on Frischknecht et al. (1996)
	disposal, building, reinforced concrete, to recycling	CH	kg	1.58E+7	1	1.55	(4,3,3,5,1,4,BU:1.05); Recycling of reinforced infrastructure; recalculated based on Frischknecht et al. (1996), assumed recycling rate: 100%
	disposal, building, reinforcement steel, to recycling	CH	kg	1.36E+6	1	1.52	(4,3,3,1,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; recalculated based Frischknecht et al. (1996), assumed recycling rate: 100%
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	4.08E+7	1	1.55	(4,3,3,5,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; recalculated based Frischknecht et al. (1996), assumed recycling rate: 100%
	transport, lorry >16t, fleet average	RER	tkm	5.84E+5	1	2.51	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Frischknecht et al. (1996)
	transport, freight, rail	RER	tkm	5.84E+5	1	2.51	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; Based on Frischknecht et al. (1996)
emission air, low population density	Heat, waste	-	MJ	5.54E+6	1	1.41	(4,5,3,5,1,5,BU:1.05); From electricity
	Particulates, < 2.5 um	-	kg	2.58E+1	1	3.61	(4,5,5,5,4,5,BU:3); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 10 um	-	kg	5.17E+2	1	2.17	(4,5,5,5,4,5,BU:1.5); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 2.5 um, and < 10um	-	kg	1.46E+2	1	2.61	(4,5,5,5,4,5,BU:2); Particle emissions during the construction; based on BUWAL (2001, 2003)

Tab. 6.6: Unit process raw data of electricity, hydropower, at run-of-river power plant, with reservoir/RER, electricity, hydropower, at run-of-river power plant, without reservoir/RER and electricity, hydropower, at run-of-river power plant, mix/RER.

	Name	Location	Unit	electricity, hydropower, at run-of-river power plant with reservoir	electricity, hydropower, at run-of-river power plant without reservoir	electricity, hydropower, at run-of-river power plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER	RER	RER			
	InfrastructureProcess			0	0	0			
	Unit			kWh	kWh	kWh			
product	electricity, hydropower, at run-of-river power plant with reservoir	RER	kWh	1					
	electricity, hydropower, at run-of-river power plant without reservoir	RER	kWh		1				
	electricity, hydropower, at run-of-river power plant	RER	kWh			1			
technosphere	electricity, hydropower, at run-of-river power plant with reservoir	RER	kWh			1.98E-2	1	1.55	(4,3,3,5,1,4,BU:1.05); Proportion of hydropower from run-of-river hydropower stations with reservoir
	electricity, hydropower, at run-of-river power plant without reservoir	RER	kWh			9.80E-1	1	1.55	(4,3,3,5,1,4,BU:1.05); Proportion of hydropower from run-of-river hydropower stations without reservoir
	run-of-river hydropower plant	RER	unit	3.25E-10	3.25E-10		1	3.70	(4,3,3,5,1,4,BU:3); Infrastructure of the run-of-river power station producing the electricity
	lubricating oil, at plant	RER	kg	1.22E-7	1.22E-7		1	1.78	(4,5,3,5,3,5,BU:1.05); In turbines; based on Axpo (2008) and Vattenfall (2008)
resource, land	Transformation, to industrial area, built up	-	m2	5.60E-7	5.60E-7		1	2.53	(4,3,3,1,1,5,BU:2); Area covered by infrastructures, not the river; based on Frischknecht et al. (1996)
	Transformation, from shrub land, sclerophyllous	-	m2	1.02E-4	2.83E-5		1	2.53	(4,3,3,1,1,5,BU:2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996)
	Transformation, from pasture and meadow	-	m2	1.02E-4	2.83E-5		1	1.67	(4,3,3,1,1,5,BU:1.2); Original area before the construction of the power station; recalculated based on Frischknecht et al. (1996)
	Transformation, to water courses, artificial	-	m2	2.04E-4	5.60E-5		1	2.53	(4,3,3,1,1,5,BU:2); Area covered by the river; recalculated based on Frischknecht et al. (1996)
	Occupation, water courses, artificial	-	m2a	1.63E-2	4.48E-3		1	1.96	(4,3,3,1,1,5,BU:1.5); Area occupied due to the run-of-river hydropower station; recalculated based on Frischknecht et al. (1996)
	Occupation, industrial area, built up	-	m2a	4.48E-5	4.48E-5		1	1.96	(4,3,3,1,1,5,BU:1.5); Area occupied due to the run-of-river hydropower station; recalculated based on Frischknecht et al. (1996)
resource, in water	Volume occupied, reservoir	-	m3a	8.24E-2			1	1.59	(4,3,3,1,1,5,BU:1.05); Volume occupied due to the run-of-river hydropower station; recalculated based on Frischknecht et al. (1996)
	Water, turbine use, unspecified natural origin	-	m3	4.50E+1	4.50E+1		1	1.59	(4,3,3,1,1,5,BU:1.05); Amount of water turbined for the generation of electricity; based on Frischknecht et al. (1996)
	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	3.79E+0		1	1.34	(3,1,1,1,1,1,BU:1.05); Potential energy of the water
emission air, unspecified	Water, OECD	-	kg	2.50E+1			1	2.27	(4,3,3,2,4,5,BU:1.5); Water evaporated from reservoir; calculated based on Pfister et al. (2011)
emission water, river	Oils, unspecified	-	kg	8.40E-8	8.40E-8		1	2.10	(4,5,3,5,3,5,BU:1.5); From turbines; based on Axpo (2008) and Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	3.80E-8	3.80E-8		1	2.10	(4,5,3,5,3,5,BU:1.5); From turbines; based on Axpo (2008) and Vattenfall (2008)
emission air, low population density	Methane, biogenic	-	kg	6.72E-4			1	1.96	(4,3,3,3,1,5,BU:1.5); Methane emissions due to the held-back river; DelSontro et al. (2010)

Tab. 6.7: Unit process raw data of small hydropower plant, in waterworks infrastructure/RER and small hydropower plant/RER.

	Name	Location	Unit	small hydropower plant, in waterworks infrastructure	small hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER	RER			
	InfrastructureProcess			1	1			
	Unit			unit	unit			
product	small hydropower plant, in waterworks infrastructure	RER	unit	1	0			
	small hydropower plant	RER	unit	0	1			
technosphere	concrete, normal, at plant	CH	m3	5.52E+1	6.30E+2	1	1.49	(4,1,3,1,1,3,BU:1.05); Infrastructure; literature
	gravel, round, at mine	CH	kg	5.21E+5	1.11E+6	1	1.49	(4,1,3,1,1,3,BU:1.05); Infrastructure; literature
	reinforcing steel, at plant	RER	kg	2.12E+3	4.99E+4	1	1.49	(4,1,3,1,1,3,BU:1.05); Infrastructure; literature
	chromium steel 18/8, at plant	RER	kg	1.01E+3	6.18E+2	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbines, generator, switchboard; literature
	steel, low-alloyed, at plant	RER	kg	1.31E+3	1.39E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbines, generator; literature
	copper, at regional storage	RER	kg	2.18E+2	2.08E+2	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbine, generatior and switchboard; literature
	polyethylene, HDPE, granulate, at plant	RER	kg	8.52E+3	9.05E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); Water pipes; literature
	polyvinylchloride, at regional storage	RER	kg	1.24E+3	1.95E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); Water pipes; literature
	cast iron, at plant	RER	kg	4.67E+4	2.72E+4	1	1.49	(4,1,3,1,1,3,BU:1.05); Water pipes; literature
	aluminium, production mix, at plant	RER	kg	2.42E+1	2.68E+1	1	1.49	(4,1,3,1,1,3,BU:1.05); Switchboard; literature
	lead, at regional storage	RER	kg	1.39E+1	1.62E+1	1	1.49	(4,1,3,1,1,3,BU:1.05); Switchboard; literature
	flat glass, uncoated, at plant	RER	kg	9.96E-1	5.63E-1	1	1.49	(4,1,3,1,1,3,BU:1.05); Switchboard; literature
	argon, liquid, at plant	RER	kg	5.85E+0	6.73E+0	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	sawn timber, softwood, raw, plant-debarked, u=70%, at plant	RER	m3	3.12E-2	3.59E-2	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	tap water, at user	RER	kg	4.03E+6	4.63E+6	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbiens; literature
	diesel, burned in building machine	GLO	MJ	6.27E+3	5.33E+4	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	electricity, medium voltage, production ENTSO, at grid	ENTSO	kWh	7.67E+2	1.02E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); Turbines; literature
	transport, lorry >16t, fleet average	RER	tkm	1.59E+4	5.45E+4	1	2.51	(4,5,na,na,na,na,BU:2); Transport of materials and waste
	transport, freight, rail	RER	tkm	3.28E+4	4.98E+4	1	2.51	(4,5,na,na,na,na,BU:2); Transport of materials and waste
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	kg	9.25E+0	1.06E+1	1	1.49	(4,1,3,1,1,3,BU:1.05); From turbines; literature
	treatment, sewage, to wastewater treatment, class 3	CH	m3	1.60E+0	1.84E+0	1	1.49	(4,1,3,1,1,3,BU:1.05); From turbines; literature
	disposal, building, reinforced concrete, to recycling	CH	kg	7.05E+4	1.43E+6	1	1.49	(4,1,3,1,1,3,BU:1.05); From infrastructure; literature
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	5.31E+4		1	1.49	(4,1,3,1,1,3,BU:1.05); From infrastructure; literature
	disposal, building, concrete gravel, to final disposal	CH	kg	5.21E+5	1.11E+6	1	1.49	(4,1,3,1,1,3,BU:1.05); From infrastructure; literature
	disposal, building, reinforcement steel, to recycling	CH	kg	2.32E+3	9.05E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); From turbines, generators, switchboards; literature
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	kg	8.52E+3	9.05E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); From water pipes; literature
	disposal, polyvinylchloride, 0.2% water, to municipal incineration	CH	kg	1.24E+3	1.95E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); From water pipes; literature
	disposal, building, bulk iron (excluding reinforcement), to sorting plant	CH	kg	4.67E+4	2.72E+4	1	1.49	(4,1,3,1,1,3,BU:1.05); From water pipes; literature
	disposal, glass, 0% water, to municipal incineration	CH	kg	9.96E-1	5.63E-1	1	1.49	(4,1,3,1,1,3,BU:1.05); From switchboards; literature
	disposal, wood untreated, 20% water, to municipal incineration	CH	kg	2.39E+1	2.75E+1	1	1.49	(4,1,3,1,1,3,BU:1.05); From turbines; literature
emission air, low population density	Heat, waste	-	MJ	7.67E+2	1.02E+3	1	1.49	(4,1,3,1,1,3,BU:1.05); From electricity

Tab. 6.8: Unit process raw data of electricity, hydropower, at small hydropower plant, in waterworks infrastructure/RER and electricity, hydropower, at small hydropower plant/RER.

	Name	Location	Unit	electricity, hydropower, at small hydropower plant, in waterworks infrastructure	electricity, hydropower, at small hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			RER	RER			
	InfrastructureProcess			0	0			
	Unit			kWh	kWh			
	electricity, hydropower, at small hydropower plant, in waterworks infrastructure	RER	kWh	1				
	electricity, hydropower, at small hydropower plant	RER	kWh		1			
	small hydropower plant, in waterworks infrastructure	RER	unit	1.23E-8		1	3.73	(4,3,3,3,3,3,BU:3); literature
	small hydropower plant	RER	unit		1.29E-8	1	3.73	(4,3,3,3,3,3,BU:3); literature
resource, in water	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	3.79E+0	1	1.60	(4,3,3,3,3,3,BU:1.05); Potenzielle Energie Wasser; literature

Tab. 6.9: Unit process raw data of reservoir hydropower plant/BR.

	Name	Location	Unit	reservoir hydropower plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			BR			
	InfrastructureProcess			1			
	Unit			unit			
product	reservoir hydropower plant	BR	unit	1			
technosphere	chromium steel 18/8, at plant	RER	kg	1.31E+7	1	1.65	(5,5,4,5,1,4,BU:1.05); Turbines and generators; based on data of the Itaipu
	excavation, hydraulic digger	RER	m3	2.36E+7	1	1.26	(4,4,1,3,1,4,BU:1.05); Excavation; based on data of the Itaipu
	explosives, tovex, at plant	CH	kg	2.24E+8	1	1.69	(5,5,4,5,1,5,BU:1.05); Tunnels and galleries; recalculated based on Béguin et al. 1963, Bertschinger 1959, Blenio Kraftwerke 1968, Condrau 1962, KVR 1963; 1968, Töndury 1956; 1964, Weber et al. 1965 and other sources.
	concrete, normal, at plant	CH	m3	3.90E+6	1	1.26	(4,4,1,3,1,4,BU:1.05); Concrete for dams, buildings and other infrastructure; based on data of the Itaipu
	reinforcing steel, at plant	RER	kg	1.26E+7	1	1.65	(5,5,4,5,1,4,BU:1.05); Buildings and other infrastructure; recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	steel, low-alloyed, at plant	RER	kg	5.51E+7	1	1.65	(5,5,4,5,1,4,BU:1.05); Tubes and pipes; recalculated based on recalculated based on Bertschinger (1959), Condrau (1962), KVR (1968), Salanfe (1951), Walther und Fetz (1963; 1971), Weber (1965; 1971) and other sources.
	copper, at regional storage	RER	kg	1.11E+8	1	1.65	(5,5,4,5,1,4,BU:1.05); Electric cables; Vattenfall (2008)
	electricity, medium voltage, at grid	BR	kWh	1.03E+10	1	1.65	(5,5,4,5,1,4,BU:1.05); Electricity supply for the construction; recalculated based on Bertschinger (1959), Blenio Kraftwerke (1968), KVR (1968), Töndury (1964), Walther und Fetz (1963), Weber et al. (1965), BFE (1992) and other sources.
	disposal, building, reinforced concrete, to recycling	CH	kg	4.19E+8	1	1.65	(5,5,4,5,1,4,BU:1.05); Recycling of reinforced infrastructure; based on Frischknecht (1996), assumed recycling rate: 100%
	disposal, building, concrete, not reinforced, to final disposal	CH	kg	8.17E+9	1	1.65	(5,5,4,5,1,4,BU:1.05); Non-inforced infrastructure left on-site at the end of the use phase of the power station (especially the dams, tunnels, galleries); based on Frischknecht et al. (1996)
	disposal, building, reinforcement steel, to recycling	CH	kg	6.83E+7	1	1.65	(5,5,4,5,1,4,BU:1.05); Recycling of turbines, generators, tubes and pipes; assumed recycling rate: 100%
	transport, lorry >32t, EURO3	RER	tkm	1.80E+9	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Bertschinger (1959)
	transport, freight, rail	RER	tkm	9.83E+9	1	2.09	(4,5,na,na,na,na,BU:2); Transport of materials to the construction site; based on Bertschinger (1959)
emission air, low population	Heat, waste	-	MJ	3.70E+10	1	1.65	(5,5,4,5,1,4,BU:1.05); From electricity
	Particulates, < 2.5 um	-	kg	2.03E+5	1	3.83	(4,5,3,5,5,5,BU:3); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 10 um	-	kg	4.05E+6	1	2.39	(4,5,3,5,5,5,BU:1.5); Particle emissions during the construction; based on BUWAL (2001, 2003)
	Particulates, > 2.5 um, and < 10um	-	kg	1.15E+6	1	2.83	(4,5,3,5,5,5,BU:2); Particle emissions during the construction; based on BUWAL (2001, 2003)

Tab. 6.10: Unit process raw data of electricity, hydropower, at reservoir power plant/BR.

	Name	Location	Unit	electricity, hydropower, at reservoir power plant	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			BR			
	InfrastructureProcess			0			
	Unit			kWh			
product	electricity, hydropower, at reservoir power plant	BR	kWh	1			
technosphere	reservoir hydropower plant	BR	unit	8.89E-14	1	3.15	(4,5,3,3,1,5,BU:3); Infrastructure of the storage power station producing the electricity
	sulphur hexafluoride, liquid, at plant	RER	kg	3.40E-13	1	1.65	(5,5,3,5,1,5,BU:1.05); In electric insulation (e.g. switches); based on Vattenfall (2008)
	lubricating oil, at plant	RER	kg	3.24E-8	1	1.65	(5,5,3,5,1,5,BU:1.05); Turbines; based on Vattenfall (2008)
resource, land	Transformation, from tropical rain forest	-	m2	1.21E-4	1	2.10	(4,1,1,3,1,5,BU:2); Original area before the construction of the power station; based on data of the Itaipu
	Transformation, to water bodies, artificial	-	m2	1.20E-4	1	2.10	(4,1,1,3,1,5,BU:2); Area covered by the reservoir; based on data of the Itaipu
	Transformation, to industrial area, built up	-	m2	1.20E-6	1	2.10	(4,1,1,3,1,5,BU:2); Area covered by infrastructures other than held-back river; recalculated based on Frischknecht et al. (1996)
	Occupation, water bodies, artificial	-	m2a	1.80E-2	1	1.62	(4,1,1,3,1,5,BU:1.5); Area occupied by the reservoir; based on data of the Itaipu
	Occupation, industrial area, built up	-	m2a	1.80E-4	1	1.62	(4,1,1,3,1,5,BU:1.5); Area occupied by the infrastructure; based on data of the Itaipu
resource, in water	Volume occupied, reservoir	-	m3a	2.53E-1	1	1.30	(4,1,1,3,1,5,BU:1.05); Volume occupied by the reservoir; ; based on data of the Itaipu
	Water, turbine use, unspecified natural origin	-	m3	2.90E-1	1	1.30	(4,1,1,3,1,5,BU:1.05); Amount of water turbined for the generation of electricity; based on data of the Itaipu
	Energy, potential (in hydropower reservoir), converted	-	MJ	3.79E+0	1	1.11	(3,1,1,1,1,1,BU:1.05); Potential energy of the water
emission air, low population density	Methane, biogenic	-	kg	5.56E-4	1	4.00	(4,3,3,3,1,3,BU:1.5); Methane emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Carbon dioxide, land transformation	-	kg	3.09E-2	1	2.00	(4,3,3,3,1,3,BU:1.4); Carbon dioxide emissions due to the biomass in the reservoirs; calculated based on Diem et al. (2008)
	Sulfur hexafluoride	-	kg	3.40E-13	1	1.90	(5,5,3,5,1,5,BU:1.5); From electric insulations (e.g. switches); based on Vattenfall (2008)
emission water, river	Oils, unspecified	-	kg	2.27E-8	1	1.90	(5,5,3,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)
emission soil, industrial	Oils, unspecified	-	kg	9.76E-9	1	1.90	(5,5,3,5,1,5,BU:1.5); From turbines; based on Vattenfall (2008)

7 Cumulative results and interpretation

7.1 Cumulative Energy Demand

The CED of the electricity generated in storage hydropower stations is around 4.22 MJ/kWh. Most of the energy demand is covered by renewable energy sources. This is due to the potential energy of the water itself. It amounts to 3.79 MJ/kWh. 10.7 % of the CED of electricity from storage hydropower stations derives from the electricity used for the operation of pumps that supply additional water to the reservoir. The dataset “storage hydropower station, CH, net” does not include the electricity consumption of pumps as an input. The electricity consumption of the pumps is subtracted from the gross electricity production of the storage hydropower plant.

Due to missing information, the electricity consumption of pumps is not considered for the European storage hydropower stations.

With around 1.1 %, the infrastructure makes only a small contribution.

The CED of the electricity generated in Swiss run-of-river hydropower stations equals 3.83 MJ/kWh and is nearly completely covered by the potential energy of the water turbined. The infrastructure contributes very little (1.1 %) to the CED.

The CED of the electricity generated in small hydropower stations is mainly covered by the potential energy of the water too (Tab. 7.2). The contribution of the infrastructure to the total CED amounts to 0.8 % for small hydropower stations that are integrated in waterworks infrastructures and 1.5 % for standalone hydropower stations.

The electricity generated in pumped storage hydropower stations in Switzerland and Europe has the highest cumulative energy demand (Fig. 7.1). Compared to the other types of hydroelectricity generation it is more than three times higher (Tab. 7.1). Nearly 100 % of the CED is due to the electricity consumption of the pumps.

There is no significant difference in the CED between Switzerland and Europe for the other types of hydroelectricity generation.

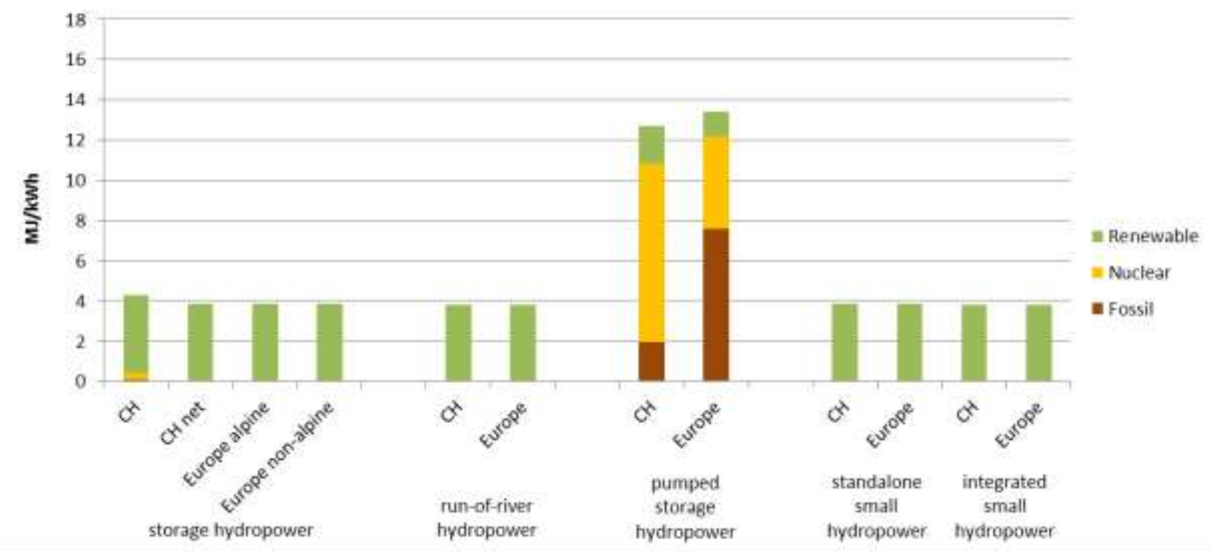

Fig. 7.1: Cumulative energy demand of the electricity generated in Swiss and European storage and run-of-river hydropower stations.
CH net: electricity consumption of pumps is subtracted from gross electricity production.

Tab. 7.1: Cumulative energy demand (in MJ oil-eq/kWh) of the storage, pumped storage and run-of-river hydroelectricity generated in Switzerland and Europe. In comparison, the total cumulative energy demand according to the ecoinvent v2.2 datasets (Bolliger & Bauer 2007).
CH net: electricity consumption of pumps is subtracted from gross electricity production.

	Storage				**Pumped storage**		**Run-of-river**	
	CH	CH net	Europe alpine	Europe non-alpine	CH	Europe	CH	Europe
Fossil	0.100	0.033	0.037	0.037	1.931	7.595	0.033	0.035
Nuclear	0.325	0.012	0.008	0.008	8.903	4.581	0.008	0.006
Renewable	3.858	3.794	3.793	3.793	1.843	1.253	3.792	3.792
Total	**4.283**	**3.838**	**3.838**	**3.838**	**12.677**	**13.428**	**3.833**	**3.833**
Total ecoinvent v2.2	3.848		3.850	3.850	14.04		3.834	3.835
Change	+11 %		0 %	0 %	-10 %		0 %	0 %

Tab. 7.2: Cumulative energy demand (in MJ oil-eq/kWh) of the hydroelectricity generated small hydropower stations in Switzerland and Europe.

	Small standalone		**Small integrated**	
	CH	Europe	CH	Europe
Fossil	0.050	0.049	0.026	0.027
Nuclear	0.007	0.007	0.003	0.003
Renewable	3.792	3.792	3.791	3.791
Total	**3.849**	**3.848**	**3.821**	**3.821**

Hydroelectricity produced in the Brazilian storage hydropower station has a total CED of 3.8 MJ/kWh. Nearly all is covered by renewable energy sources, most of it by the potential energy of the water turbined. The infrastructure accounts for 0.2 %.

In comparison with electricity from hydropower according to the current ecoinvent data sets (Bolliger & Bauer 2007), the CED of the electricity from Swiss storage hydropower stations increases by 11 %. This is mainly due to the additional consideration of the electricity consumption of various pumps (excluding pumped storage pumps). This is supported by the CED of electricity from storage hydropower stations where only the net production and hence no electricity consumption is considered. Their CED is similar to the ecoinvent data modelled by Bolliger & Bauer (2007).

As the electricity consumption of the pumps is not considered for European storage hydropower stations, their CED does not change. The material consumption per hydropower station is lower than in the existing data sets as the hydropower stations are smaller (lower capacity). On the other hand, less electricity is generated in these plants. The material consumption per kWh electricity produced is therefore about the same. The average run-of-river hydropower station modelled in this study is smaller too. However the material intensity per kWh electricity produced remains about the same.

7.2 Greenhouse gas emissions

In Fig. 7.2 the greenhouse gas emissions of different types of hydroelectricity generation in Switzerland and Europe are compared. The electricity from pumped storage hydropower stations is omitted due to its high emission factors and a better readability of the figure. All the greenhouse gas emissions and other impact category indicator results are listed in Tab. 7.3.

Electricity generated in storage hydropower stations in Switzerland causes emissions of 10.8 g CO_2-eq/kWh. 50 % of these emissions are caused by the electricity consumption in pumps during the operation of the station. The emissions from the reservoirs cover 12.8 % of the total emissions. The rest is contributed by the construction of the stations. The importance of the electricity is apparent if the storage hydropower stations are compared to the storage hydropower stations where only the net production is considered. Their greenhouse gas emissions are half as high.

Due to the larger surface area of the non-alpine reservoirs as well as a different climate, the greenhouse gas emissions are significantly higher than from alpine reservoirs. The emissions from the reservoirs contribute 73 % to the total greenhouse gas emissions.

The greenhouse gas emissions of the electricity generation in pumped storage hydropower stations are strongly dominated by the electricity generation of the pumps. In Switzerland, this is 96.6 %, in Europe it is 99.1 %. The emissions from the reservoirs account for 0.9 % of the greenhouse gas emissions from Swiss pumped storage hydropower stations and for 0.2 % from the European ones.

The greenhouse gas emissions of 1 kWh electricity produced in run-of-river hydropower stations are dominated by the infrastructure (92 %). The rest stems from the emissions from the reservoirs.

The electricity from small hydropower stations causes greenhouse gas emissions of 4.9 g CO_2-eq/kWh and 1.9 g CO_2-eq/kWh for stand-alone and integrated small hydropower, respectively (Tab. 7.4). All emissions derive from the infrastructure. Consequently, the electricity from small hydropower stations integrated in existing waterworks infrastructures causes fewer emissions than the electricity from standalone small hydropower stations.

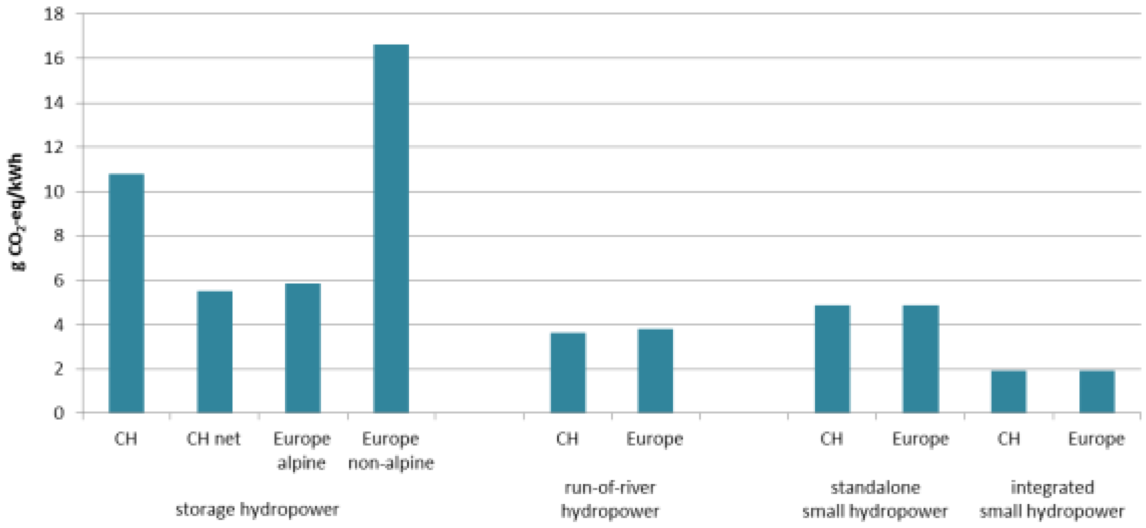

Fig. 7.2: Greenhouse gas emissions of the electricity generated in Swiss and European storage and run-of-river hydropower stations. The emissions of pumped storage hydroelectricity are not shown due to the relatively high values and for a better readability. CH net: electricity consumption of pumps is subtracted from gross electricity production.

Tab. 7.3: Greenhouse gas emissions and other impact category indicator results of the storage, pumped storage and run-of-river hydroelectricity generated in Switzerland and Europe. In comparison, the total cumulated energy demand of the ecoinvent v2.2 datasets (Bolliger & Bauer 2007).
CH net: electricity consumption of pumps is subtracted from gross electricity production.

		Storage				**Pumped storage**		**Run-of-river**	
		CH	CH net	Europe alpine	Europe non-alpine	CH	Europe	CH	Europe
Abiotic depletion	g Sb eq	0.056	0.017	0.020	0.020	1.111	4.485	0.018	0.019
Acidification	g SO_2 eq	0.032	0.013	0.015	0.015	0.555	2.295	0.013	0.014
Eutrophication	g PO_4^{3-} eq	0.018	0.005	0.006	0.006	0.373	1.685	0.006	0.006
Global warming	**g CO_2 eq**	**10.78**	**5.513**	**5.858**	**16.64**	**155.1**	**609.2**	**3.617**	**3.793**
Ozone layer depletion	µg CFC-11 eq	0.001	0.000	0.000	0.000	0.020	0.024	0.000	0.000
Human toxicity	g 1,4-DB eq	12.72	8.044	8.138	8.138	140.9	265.5	7.524	7.573
Fresh water aq. ecotox.	g 1,4-DB eq	4.332	1.806	1.963	1.963	73.6	276.4	1.964	2.047
Marine aq. Ecotoxicity	kg 1,4-DB eq	8.145	2.863	3.203	3.203	152.9	591.1	3.108	3.287
Terrestrial Ecotoxicity	g 1,4-DB eq	0.041	0.023	0.023	0.023	0.531	1.182	0.029	0.029
Photochem. Oxidation	g C_2H_4	0.001	0.001	0.001	0.001	0.024	0.096	0.001	0.001
Global warming ecoinvent v2.2	g CO_2 eq.	5.23	-	5.68	11.6	189	-	3.51	3.70
Change		+106%	-	+3 %	+43 %	-18 %	-	+3 %	+3 %

Tab. 7.4: Greenhouse gas emissions and other impact category indicator results of the hydroelectricity generated in small hydropower stations in Switzerland and Europe.

		Small standalones		**Small integrated**	
		CH	Europe	CH	Europe
Abiotic depletion	g Sb eq	0.027	0.027	0.015	0.015
Acidification	g SO_2 eq	0.014	0.014	0.006	0.006
Eutrophication	g PO_4^{3-} eq	0.006	0.006	0.003	0.003
Global warming	**g CO_2 eq**	**4.888**	**4.876**	**1.918**	**1.928**
Ozone layer depletion	µg CFC-11 eq	0.000	0.000	0.000	0.000
Human toxicity	g 1,4-DB eq	2.950	2.952	2.525	2.529
Fresh water aq. ecotox.	g 1,4-DB eq	1.957	1.969	1.538	1.548
Marine aq. Ecotoxicity	kg 1,4-DB eq	2.777	2.802	2.074	2.094
Terrestrial Ecotoxicity	g 1,4-DB eq	0.048	0.048	0.043	0.043
Photochem. Oxidation	g C_2H_4	0.001	0.001	0.001	0.001

While the greenhouse gas emissions of the electricity produced in storage hydropower stations in Switzerland is dominated by the electricity consumption, the emissions from the reservoirs contribute 99 % to the total greenhouse gas emissions of electricity produced in Brazilian storage hydropower stations (43 g CO_2-eq/kWh). The infrastructure contributes 1 %.

A comparison with the current ecoinvent data sets (Bolliger & Bauer 2007) shows an increase in greenhouse gas emissions of the electricity produced in Swiss storage hydropower stations. This increase is based on the implementation of the electricity consumption during the operation of the power stations. Otherwise the greenhouse gas emissions remain constant. The significant increase in the greenhouse gas emissions of the European non-alpine electricity production from storage hydropower plants is due to the implementation of CO_2- and N_2O-emissions from the reservoir.

The level of greenhouse gas emissions from pumped storage hydropower stations is slightly lower.

The greenhouse gas emissions of the electricity generated in run-of-river hydropower stations increase slightly. This is due to the consideration of greenhouse gas emissions from reservoirs.

Environmental impacts caused by electricity generation in small hydropower stations cannot be compared to respective ecoinvent datasets as there are no data are about the electricity generation in small hydropower stations available.

References

Aegerter et al. 1954	Aegerter et al. (1954) Das Kraftwerk Birsfelden. *In: Wasser- und Energiewirtschaft*, **46**(5-7), pp. 165-176.
Aegina 1965	Aegina (1965) Die Anlagen der Kraftwerk Aegina AG, mitgeteilt von der Ingenieurgemeinschaft Schweiz, Aluminium-Industrie AG und Maggia-Kraftwerke AG. *In: Kraftwerkbau*, **9**(3-4), pp. 1-20.
Axpo 2008	Axpo (2008) Umweltdeklaration: Niederdruckwasserkraftwerk Wildegg-Brugg.
Baumann 1949	Baumann (1949) Kraftwerk Rupperswil-Auenstein. Verlag Kraftwerk Rupperswil-Auenstein A.G., Rupperswil.
Baumgartner & Doka 1998	Baumgartner W. and Doka G. (1998) Energiebilanzen von Klein-Wasserkraftwerken; Energierückzahldauern - Energieerntefaktoren. 2. Auflage, DIANE 10 Klein-Wasserkraftwerke, ITECO Ingenieurunternehmung AG, Affoltern am Albis.
Béguin & Jeanneret 1963	Béguin and Jeanneret (1963) Aménagement de la Dranse d'Entremont. *In: Wasser- und Energiewirtschaft*, **55**(8), pp. 265-274.
Berg & Real 2006	Berg M. and Real M. (2006) Road Map Erneuerbare Energien Schweiz. SATW-Schrift Nr. 39. Schweizerische Akademie der Technischen Wissenschaften, SATW, Zürich, retrieved from: www.satw.ch.
Bertschinger 1959	Bertschinger (1959) Versorgungs- und Transportprobleme beim Bau der Bergeller Kraftwerke der Stadt Zürich. *In: Wasser- und Energiewirtschaft*, **51**(7), pp. 191-198.
BFE 1992	BFE (1992) Schweizerische Gesamtenergiestatistik 1991. In: *Bulletin SEV/VSE*, Vol. 12 (ed. Elektrizitätswerke V. S.). Bundesamt für Energie, Bern, CH.
BFE 2010a	BFE (2010a) Schweizerische Elektrizitätsstatistik 2009. Bundesamt für Energie, Bern, CH, retrieved from: http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=de&dossier_id=04840.
BFE 2010b	BFE (2010b) Statistik der Wasserkraftanlagen der Schweiz (ed. UVEK), Bern.
BFE 2011a	BFE (2011a) Schweizerische Elektrizitätsstatistik 2010. Bundesamt für Energie, Bern, CH, retrieved from: http://www.bfe.admin.ch/themen/00526/00541/00542/00630/index.html?lang=de&dossier_id=04840.
BFE 2011b	BFE (2011b) Gesamte Erzeugung und Abgabe Elektrischer Energie in der Schweiz 2010.
BFE 2011c	BFE (2011c) Statistik der Wasserkraftanlagen der Schweiz (ed. UVEK), Bern.

Biedermann et al. 1985	Biedermann et al. (1985) Barrages Suisses, Swiss Dams. In: *15^{e} Congrès International des Grands Barrages 1985 à Lausanne*. Comité National Suisse des Grands Barrages, Zürich.
Binacional 2000	Binacional I. (2000) Itaipu: Eines der Sieben Wunder der Neuzeit (ed. Binacional I.), retrieved from: www.itaipu.gov.py.
Bischof 1992	Bischof (1992) Modernisierungspotential bie bestehenden Wasserkraftwerken. In: *Vortrag beim Schweiz. Technischen Verband, Sektion Graubünden*, Churwalden.
Blenio Kraftwerke 1968	Blenio Kraftwerke (1968) Der Ausbau der Blenio Kraftwerke, Mitteilung der Geschäftsleitung der Blenio Kraftwerke AG. *In: Wasser- und Energiewirtschaft*, **60**(7-8), pp. 211-216.
Bolliger & Bauer 2007	Bolliger R. and Bauer C. (2007) Wasserkraft. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz*, Vol. ecoinvent report No. 6-VIII, v2.0 (Ed. Dones R.). Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH retrieved from: www.ecoinvent.org.
Bratrich & Truffer 2001	Bratrich C. and Truffer B. (2001) Ökostrom-Zertifizierung für Wasserkraftanlagen.
Brux 1983	Brux (1983) Das Donaukraftwerk Greifenstein. *In: Wasser, Energie, Luft*, **75**(1-2), pp. 11-13.
BUWAL 2001	BUWAL (2001) Massnahmen zur Reduktion der PM10-Emissionen. Umwelt-Materialien Nr. 136. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.
BUWAL 2003	BUWAL (2003) Modelling of PM10 and PM2.5 ambient concentrations in Switzerland 2000 and 2010. Environmental Documentation No. 169. Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern.
BWW 1973	BWW (1973) Statistik der Wasserkraftanlagen der Schweiz auf 1. Januar 1973. Eidg. Amt für Wasserwirtschaft, Bern.
Condrau 1962	Condrau (1962) Die Kraftwerke Vorderrhein. *In: Terra Grischuna*, **21**(5), pp. 352-355.
DelSontro et al. 2010	DelSontro, McGinnis, Sobek, Ostrovsky and Wehrli (2010) Extreme Methane Emissions from a Swiss Hydropower Reservoir: Contribution from Bubbling Sediments. *In: Environ Sci. Technol.*, **44**, pp. 2419-2425.
DesMeules 1961	DesMeules (1961) Barrage-poids de la Grande Dixence. *In: Wasser- und Energiewirtschaft*, **53**(6-7), pp. 177-182.
Diem et al. 2008	Diem, Koch, Schwarzenbach, Wehrli and Schubert (2008) Greenhouse gas emissions (CO2, CH4 and N2O) from peri-alpine and alpine hydropower reservoirs. *In: Biogeosciences Discuss.*, **5**, pp. 3699-3736, 10.5194/bgd-5-3699-2008.

Doka 2009 Doka G. (2009) Life Cycle Inventories of Waste Treatment Services. ecoinvent report No. 13, v2.1. EMPA St. Gallen, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

dos Santos et al. 2006 dos Santos M. A., Rosa L. P., Sikar B., Sikar E. and dos Santos E. O. (2006) Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *In: Energy Policy*, **34**, pp. 481-488.

Engel et al. 1985 Engel, Fehle and Hartman (1985) Ein altes Wasserkraftwerk, was nun? *In: Bulletin des Schweizerischen Elektrotechnischen Vereins (SEV) und des Verbandes Schweizerischer Elektrizitätswerke (VSE)*, **76**(22), pp. 1358-1363.

Erbiste 1984 Erbiste (1984) Estimating gate weights. *In: Water Power & Dam Construction*, **36**(5), pp. 18-23.

EUROSTAT 2010 EUROSTAT (2010) Energy - Yearly statistics 2008.

Fearnside 2004 Fearnside (2004) Greenhouse Gas Emissions from Hydroelectric Dams: Controversies Provide a Springboard for Rethinking a Supposedly "clean" Energy Source. *In: Climatic Change*, pp.

Frischknecht et al. 1994 Frischknecht R., Hofstetter P., Knoepfel I., Dones R. and Zollinger E. (1994) Ökoinventare für Energiesysteme. Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 1. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut Villigen, Bundesamt für Energie (Hrsg.), Bern.

Frischknecht et al. 1996 Frischknecht R., Bollens U., Bosshart S., Ciot M., Ciseri L., Doka G., Dones R., Gantner U., Hischier R. and Martin A. (1996) Ökoinventare von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. 3. Gruppe Energie - Stoffe - Umwelt (ESU), Eidgenössische Technische Hochschule Zürich und Sektion Ganzheitliche Systemanalysen, Paul Scherrer Institut, Villigen, Bundesamt für Energie (Hrsg.), Bern, CH, retrieved from: www.energieforschung.ch.

Frischknecht et al. 2007 Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Gicot 1956 Gicot (1956) Le comportement du barrage de Rossens durant les premières années d'exploitation. *In: Wasser- und Energiewirtschaft*, **48**(7-9), pp. 280-285.

Herbeck & Reismann 1977 Herbeck and Reismann (1977) Die Bauausführung grosser Talsperren und Staustufen. *In: Österreichische Wasserwirtschaft*, **29**(9-10), pp. 243-264.

IEA 2011 IEA (2011) Monthly Electricity Statistics (ed. OECD), Paris.

Jean-Baptiste & Konersmann 2000	Jean-Baptiste D. and Konersmann L. (2000) Lokale und globale Umweltauswirkungen der Wasserkraftanlage Guarda. semester thesis. ETH Zürich, Zürich.
König 1985	König (1985) Bau von Wasserkraftanlagen. C.F. Müller, Karlsruhe.
KVR 1963	KVR (1963) Die Kraftwerke Vorderrhein im Bündner Oberland, Hg. von der Kraftwerke Vorderrhein AG Disentis zur Einweihung am 27. Juni 1963.
KVR 1968	KVR (1968) Die Kraftwerke Vorderrhein im Bünder Oberland. *In: Kraftwerkbau*, **13**(1), pp. 5-30.
Lima 2005	Lima (2005) Biogeochemical distinction of methane releases from two Amazon hydroreservoirs. *In: Chemosphere*, **59**(11), pp. 1697-1702.
Link 1970	Link (1970) Die Speicherseen der Alpen. *In: Wasser- und Energiewirtschaft*, **62**(9), pp. 241-358.
Mäkinen & Khan 2010	Mäkinen and Khan (2010) Policy Considerations for Greenhouse Gas Emissions from Freshwater Reservoirs. *In: Water Alternatives*, **3**(2), pp. 91-105.
Meyer 1960	Meyer E. (1960) Erfahrungen beim Bau der Misoxer Kraftwerke. *In: Kraftwerkbau*, **5**(Nov.-Dez.), pp. 85-105.
Morf 1962	Morf (1962) Kraftwerke Linth-Limmern. *In: Kraftwerkbau*, **7**(1), pp. 11-24.
NOK 1956	NOK (1956) Das Kraftwerk Wildegg-Brugg. *In: Schweizerische Bauzeitung*, **74**(4;5;5;7;8;10;12), pp. 47-52;63-67;83-88;93-99;111-116;145-147;167-172.
Pfister et al. 2011	Pfister S., Saner D. and Koehler A. (2011) The environmental relevance of freshwater consumption in global power production. *In: Int J LCA*, pp. 1-12.
Programm Kleinwasserkraftwerke 2010	Programm Kleinwasserkraftwerke (2010) Pressemappe Kleinwasserkraftwerk.
Radag 1979	Radag (1979) 50 Jahre Rheinkraftwerk Albbruck-Dogern Aktiengesellschaft, 1929-1979.
Rosa et al. 2003	Rosa et al. (2003) Biogenic gas production from major Amazon reservoirs, Brazil. *In: Hydrological Processes*, **17**(7), pp. 1443-1450.
Rosa et al. 2004	Rosa L. P., dos Santos M. A., Matvienko B., dos Santos E. O. and Sikar E. (2004) Greenhouse gases emissions by hydroeletric reservoirs in tropical regions. *In: Climatic Change*, **66**(1-2), pp. 9-21.
Salanfe 1951	Salanfe (1951) Das Speicherkraftwerk Salanfe-Miéville. *In: Schweizerische Bauzeitung*, **69**(52), pp. 735-744.
Schnitter 1961	Schnitter (1961) Zervreila Arch Dam. *In: Water Power*, **13**(4), pp. 129-138.
Schnitter 1971	Schnitter (1971) Staumauer und Machinenhaus Ova Spin der Engadiner Kraftwerke AG. *In: Schweizerische Bauzeitung*, **89**(33), pp. 811-816.

Schweizerisches Talsperrenkomitee 2011 Schweizerisches Talsperrenkomitee (2011) Verzeichnis der Schweizer Talsperren retrieved from: http://www.swissdams.ch/Dams/damList/default_d.asp?Sort=HauteurDesc.

Sinniger et al. 1991 Sinniger et al. (1991) Ageing of dams - Swiss experience. *In proceedings from: Commission Internationale des Grands Barrages, Dix-septième Congrès des Grands Barrages*, Vienna.

Soumis et al. 2005 Soumis, Lucotte, Canuel, Weissenberger, Houel, Larose and Duchemin (2005) Hydroelectric reservoirs as anthropogenic sources of greenhouse gases. *In: Water Encyclopedia*, **1-4**, pp. 203-210.

Spreafico & Weingartner 2005 Spreafico M. and Weingartner R. (2005) Hydrologie der Schweiz - Ausgewählte Aspekte und Resultate. Bundesamt für Wasser und Geologie (BWG), Bern.

St.Louis et al. 2009 St.Louis V., Kelly C. A., Duchemin E., Rudd J. W. M. and Rosenberg D. M. (2009) Reservoir Surfaces as Sources of Greenhouse Gases to the Atmosphere: A Global Estimate. *In: BioScience*, **50**(9), pp. 766-775.

Stambach 1944 Stambach (1944) Über die Entwicklung der schweizerischen Niederdruck-Wasserkraftanlagen in den letzten 50 Jahren. *In: Schweizerische Bauzeitung*, **124 125**(25 26), pp. 321-325 336-340.

Stucky 1962 Stucky (1962) L'aménagement hydro-électrique de la Gougra. Les barrages de Moiry et de Tourtemagne, A. Le barrage de Moiry. *In: Schweizerische Bauzeitung*, **80**(20, 21), pp. 335-342, 353-356.

Töndury 1956 Töndury (1956) Besuch bei den Bergeller Kraftwerken der Stadt Zürich. *In: Wasser- und Energiewirtschaft*, **48**(12), pp. 356-363.

Töndury 1964 Töndury (1964) Einweihung der Kraftwerkgruppe Blenio. *In: Wasser- und Energiewirtschaft*, **56**(12), pp. 398-403.

Vattenfall 2008 Vattenfall (2008) Certified Environmental Product Declaration of Electricity from Vattenfalls's Nordic Hydropower, retrieved from: www.vattenfall.com.

Walther & Fetz 1963 Walther and Fetz (1963) Sondernummer zur Einweihung der Kraftwerkanlagen Hinterrhein-Valle di Lei. *In: Terra Grischuna*, **22**(4), pp. 153-348.

Walther & Fetz 1971 Walther and Fetz (1971) Engadiner Kraftwerke. *In: Terra Grischuna*, **30**(4), pp. 159-216.

Weber et al. 1965 Weber et al. (1965) Die Kraftwerke Linth-Limmern. *In: Kraftwerkbau*, **10**(2-3), pp. 1-23.

Weber et al. 1970 Weber et al. (1970) Kraftwerkbau am Vorderrhein. *In: Wasser- und Energiewirtschaft*, **62**(7-8), pp. 199-218.

Weber et al. 1971 Weber et al. (1971) Kraftwerkbau am Vorderrhein. *In: Wasser- und Energiewirtschaft*, **62**(7-8), pp. 199-218.

Wunderle 1984	Wunderle (1984) Der elektro-maschinelle Bereich in 30 Jahren Donauausbau - bewährte Strukturen und neue Techniken. *In: Österreichische Zeitschrift für Elektrizitätswirtschaft*, **37**(5-6), pp. 142-150.
Zingg 1961	Zingg (1961) Die Bergeller Kraftwerke der Stadt Zürich. *In: Terra Grischuna*, **20**(4), pp. 233-258.

Appendix

Tab. 0.1 Some data of the storage power stations considered (Aegina 1965; Béguin & Jeanneret 1963; Bertschinger 1959; BFE 1992; Biedermann et al. 1985; Blenio Kraftwerke 1968; BWW 1973; Condrau 1962; DesMeules 1961; Gicot 1956; KVR 1963, 1968; Link 1970; Meyer 1960; Morf 1962; Salanfe 1951; Schnitter 1961, 1971; Stucky 1962; Töndury 1956, 1964; Walther & Fetz 1963, 1971; Weber et al. 1965, 1970; Zingg 1961).

Name of dam	Name of station	Name of group	Length of damm	Catchment area	Length of reservoir	Surface area	Volume of reservoir	Height of dam	Net drop height	Installed capacity	Net production	Cement for injection etc.
			m	km2	km	ha	mio m3	m	m	MW	GWh	1000 kg
Albigna	Bondo	Bergell	759	20.5	2	126	71	115	271	6.7	19.06	3700
		Bergell							711			
		Bergell										
		Bergell							345			
		Bergell							662			
		Bergell							543			
		Bergell										
		Bergell										
Gebidem	Bitsch (Biel	Bitsch	327	150.3	1.4	21	9.2	122	683	340	556	2724
Malvaglia	Biasca	Blenio	292	61.3	1.1	19	4.6	92	644	324	688	210
Carassina	Luzzone	Blenio	115	16.5	0.6	3	0.31	39	141	20	26.8	
Luzzone	Olivone	Blenio	600	36.74	3.1	144	108	225	479	102	210.1	
Molina	Sassello	Calancasca	93	135	0.5	7	0.81	54	389	20.8	89.4	
Les Toules	Orières	Drance d'E.	460	37.6	2	61	20.15	86	364			1850
	Pallazuit	Drance d'E.							432	33.4	107	
	Tsi	Drance d'E.										
Vieux Emosson	Châtelard-Barberine I+II	Emosson	125		0.2	2.2	0.25	33		112	148	
Emosson	Châtelard-Vallorcine	Emosson	555	34.91	4	327	227	180		260.5	410	11465
	La Bâtiaz	Emosson								170	415	
	usw.	Emosson										
Punt dal Gall	Ova spin	Engadin	540	295	9	471	164.6	130	120	54	87.4	8600
	Ova Spin-Dotierzentrale	Engadin							40	0.47	1.57	
Ova Spin	Pradella	Engadin	130	385	4	36	7.4	73	463	300	1020	725
	Punt dal Gall	Engadin							59	2.8	5.45	
Vasasca	Guimaglio	Guimaglio	107	14	0.4	1.5	0.4	69	340	8.94	25.3	1050
Göschenenreuss	Paffensprung	Göschenen	70	49.8	0.2		0.1	36		58	290	
	usw.	Göschenen								164.8	431.8	
	Chippis (Navisence)	Gougra							569	99.84	553	
Moiry	Mottec	Gougra	610	29	2.4	140	78	148	607			4854
Turtmann	Mottec	Gougra	110	28.1	0.2	10	0.8	32		71	135	
	Vissoie	Gougra							426	50	210	
	Vissoie	Gougra							426	0.68	0	
Cleuson	Chandoline	Grande Dixence	420	16	1.4	50	20	87				
Grande Dixence	Chandoline	Grande Dixence	695	43.6	5.3	430	401	285		150	115	
	Fionnay	Grande Dixence								306	370	
Mauvoisin	Fionnay	Grande Dixence	520	113.5	4.9	208	211.5	250		140	275.8	9600
	Bieudron	Grande Dixence								1285	1235	
	Nendaz	Grande Dixence								392	455	
	Chanrion	Grande Dixence								30	72	
	Riddes	Grande Dixence								258	667.8	
Z'Mutt	Z'Mutt	Grande Dixence	144	56.4	0.6	4	0.85	74				
	Cleuson	Grande Dixence										
	Stafel	Grande Dixence										
	Ferpercle	Grande Dixence										
	Arolla	Grande Dixence										
Roggiasca	Grono	Grono	177	11.7	0.3	3	0.52	68	602	37.5	93.96	
Rossens	Hauterive	Hauterive	320	954	13.5	960	220	83	83	60	205	
Sufers	Bärenburg	Hinterrhein	125	194	2.2	94	17.5	58	306	220	491	948
	Bärenburg	Hinterrhein							40	0.76	2.8	
Valle di Lei	Ferrera I	Hinterrhein	690	46.5	7.7	410	197	141	460	180	308	3930
	Ferrera II	Hinterrhein							45	4.4	2.5	
Bärenburg	Sils (KHR)	Hinterrhein	110	460	0.8	7.5	1	64	383	247	646	368
Hongrin	Veytaux	Hongrin	325	45.6	2.7	160	53.2	125	823	240	186	
Châtelot	Le Châtelot	Le Châtelot	150	911	3.3	69	20.6	74	75	32.6	106.35	
Les Clées	Les Clées	Les Clées	100	288	1.4	8	0.74	32	141	30	103	
	Chamarin	Lienne							320	1.9	0.6	
Zeuzier	Croix	Lienne	256	18.7	1.3	85	51	156	766	66	147	1860
	St. Léonard	Lienne							393	36	93	
	Linthal (Limmern)	Linth-Limmern							125	34.4	81.1	
	Tierfehd (Hintersand)	Linth-Limmern							470	42	83	
Limmern	Tierfehd (Limmern)	Linth-Limmern	375	17.8	3	136	93	146	963	261	283.7	16000
Lucendro	Airolo	Lucendro	269	7.05	1.4	54	25	73	938	60	102.3	242
Sella	Airolo	Lucendro	334	6.7	1.4	45	9.2	36		1.93	2.9	309
	Tremola/Sella	Lucendro										
Gries	Altstafel	Maggia	400	10.6	0.9	55.5	18.6	60	371	9.67	21.6	
Robiei	Bavona	Maggia	360	1.52	0.5	24	6.7	68	854	140	324.3	
Zöt	Bavona	Maggia	145	9.5	0.5	13	1.65	36				
	Cavergno	Maggia							482	114	397.7	
Sambuco	Peccia (Sambuco)	Maggia	363	29.75	3	111	63	130	359	54	85.4	
Cavagnoli	Robiei	Maggia	320	5.05	0.9	46	29	111	352	173	37.4	
Naret I+II	Robiei	Maggia	700	4.05	1.1	73	31.6	125				
Palagnedra	Verbano I	Maggia	207	137.7	2.2	25	4.26	72	253	119	346.3	
	Verbano II	Maggia							272	62	160.4	
	Soazza	Mesolcina							698	83	245.1	
Isola	Spina (Isola)	Mesolcina	290	43	2	39	6.5	45	392	20.9	62.8	145
Carmena	Morobbia	Morobbia	100	23	0.4	2.4	0.3	40	351	15.5	42.4	
Oberaar	Grimsel I (Oberarr)	Oberhasli	526	19.4	2.8	146	61	100		35.3	48.2	
Räterichsboden	Handeck II	Oberhasli	456	130.2	1.7	67	27	94		136	370	
	Handeck III	Oberhasli								55	55.4	
	Handeck I	Oberhasli								100	51	
	Innerkirchen I	Oberhasli								239.5	784.1	
	Hopflauenen	Oberhasli								91.4	276.1	
	usw.	Oberhasli										
	Clusanfe	Salanfe										
	Giétroz du Fond	Salanfe										
Salanfe	Miéville	Salanfe	616	18.4	2	185	40	52	1332	60	110.4	
Sanetsch	Innergsteig	Sanetsch	215	10.7	0.9	29	2.8	42	825	19.6	38.1	
Schiffenen	Schiffenen	Schiffenen	417	1400	12.7	425	65	47	43	71	139	
Contra	Gordola	Verzasca	380	233	5.5	168	105	220	227	132.5	215	
	Tenero	Verzasca							247	4.25	12	
Curnera	Sedrun	Vorderrhein	350	24.1	2	81	41.1	153		150	261.4	1092
Nalps	Sedrun	Vorderrhein	480	22.3	2	91	45	127		0.75	2.9	707
Sta. Maria	Sedrun	Vorderrhein	560	27.1	3	177	67.3	117	539			547
Runcahez	Tavanasa	Vorderrhein	182	54.8	0.5	5	0.48	33	453	180	563.4	
	Rothenbrunnen	Zervreila							631	44	204.57	
	Safien Platz	Zervreila							399	90	162.3	
Zervreila	Zervreila	Zervreila	504	63.9	4	161	100.5	151	79	22	25.7	3799
Egschi	Realta	Zervreila	80	107.7	0.6	7	0.4	40	510	26	38.8	
Total			17554	6860.07	131.5	6023.1	2731.92	5049	25316	8565	16639	74725

Name of dam	Name of station	Name of group	Volume dam	Injection/ volume dam	Cement in concrete min	Cement in concrete max	Cement in concrete avg	Cement for dam	Zement dam + injection	Cement f. dam + inj. of group	Cement tot. incl. tunnels	Cement dam/total	Remeining cement
			1000m3	kg/m3	kg/m3	kg/m3	kg/m3	Mio kg	Mio kg	Mio kg	Mio. kg		Mio kg
Albigna	Bondo	Bergell	926	3.996	140	250	172	159.272	162.972	162.972	220	74%	57.028
		Bergell											
		Bergell											
		Bergell											
		Bergell											
		Bergell											
		Bergell											
		Bergell											
Gebidem	Bitsch (Biel	Bitsch	228	11.947	200	250	233	53.124	55.848	55.848	79	71%	23.152
Malvaglia	Biasca	Blenio	162	1.296	200	250	233	37.746	37.956	349.846	440	80%	90.154
Carassina	Luzzone	Blenio	9					2	2				
Luzzone	Olivone	Blenio	1330		200	250	233	309.89	309.89				
Molina	Sassello	Calancasca	14					3	3	3	5	60%	2
Les Toules	Orières	Drance d'E.	235	7.872	250	300	250	58.75	60.6	60.6	85	71%	24.4
	Pallazuit	Drance d'E.											
	Tsi	Drance d'E.											
Vieux Emosson	Châtelard-Barberine I+II	Emosson											
Emosson	Châtelard-Vallorcine	Emosson	1090	10.518	160	250	198	215.82	227.285				
	La Bâtiaz	Emosson											
	usw.	Emosson											
Punt dal Gall	Ova spin	Engadin	776	11.082	180	250	227	176.152	184.752	192.227	320	60%	127.773
	Ova Spin-Dotierzentrale	Engadin											
Ova Spin	Pradella	Engadin	27	26.852	250	250	250	6.75	7.475				
	Punt dal Gall	Engadin											
Vasasca	Guimaglio	Guimaglio	21	50.000	250	250	257	5.397	6.447	6.447	9	72%	2.553
Göschenenreuss	Paffensprung	Göschenen	11					3	3	3	4	75%	1
	usw.	Göschenen											
	Chippis (Navisence)	Gougra								180.961	255	71%	74.039
Moiry	Mottec	Gougra	815	5.956	160	260	215	175.225	180.079				
Turtmann	Mottec	Gougra	3		250	300	294	0.882	0.882				
	Vissoie	Gougra											
	Vissoie	Gougra											
Cleuson	Chandoline	Grande Dixence	400					92	92	1596.81	2251	71%	654.19
Grande Dixence	Chandoline	Grande Dixence	6000		140	250	178	1068	1068				
	Fionnay	Grande Dixence											
Mauvoisin	Fionnay	Grande Dixence	2030	4.729	175	250	207	420.21	429.81				
	Bieudron	Grande Dixence											
	Nendaz	Grande Dixence											
	Chanrion	Grande Dixence											
	Riddes	Grande Dixence											
Z'Mutt	Z'Mutt	Grande Dixence	32					7	7				
	Cleuson	Grande Dixence											
	Stafel	Grande Dixence											
	Ferpercle	Grande Dixence											
	Arolla	Grande Dixence											
Roggiasca	Grono	Grono	32					7	7	7	10	70%	3
Rossens	Hauterive	Hauterive	255		250	250	250	63.75	63.75	63.75	90	71%	26.25
Sufers	Bärenburg	Hinterrhein	22	43.091	250	250	250	5.5	6.448	234.631	359	65%	124.369
	Bärenburg	Hinterrhein											
Valle di Lei	Ferrera I	Hinterrhein	862	4.559	230	275	250	212.5	216.43				
	Ferrera II	Hinterrhein											
Bärenburg	Sils (KHR)	Hinterrhein	55	6.691	170	280	207	11.385	11.753				
Hongrin	Veytaux	Hongrin	235		250	250	250	58.75	58.75	58.75	83	71%	24.25
Châtelot	Le Châtelot	Le Châtelot	48		270	300	280	13.44	13.44	13.44	19	71%	5.56
Les Clées	Les Clées	Les Clées	21					5	5	5	7	71%	2
	Chamarin	Lienne								68.76	97	71%	28.24
Zeuzier	Croix	Lienne	300	6.200	170	250	223	66.9	68.76				
	St. Léonard	Lienne											
	Linthal (Limmern)	Linth-Limmern								144.849	240	60%	95.151
	Tierfehd (Hintersand)	Linth-Limmern											
Limmern	Tierfehd (Limmern)	Linth-Limmern	553	28.933	200	250	233	128.849	144.849				
Lucendro	Airolo	Lucendro	154	1.571	230	270	258	39.732	39.974	57.007	63	90%	5.993
Sella	Airolo	Lucendro	74	4.176			226	16.724	17.033				
	Tremola/Sella	Lucendro											
Gries	Altstafel	Maggia	251		200	280	220	55.22	55.22	428.861	1203	36%	774.139
Robiei	Bavona	Maggia	180					41	41				
Zöt	Bavona	Maggia	16					4	4				
	Cavergno	Maggia											
Sambuco	Peccia (Sambuco)	Maggia	775		170	260	230	178.25	178.25				
Cavagnoli	Robiei	Maggia	223		200	250	217	48.391	48.391				
Naret I+II	Robiei	Maggia	372					85	85				
Palagnedra	Verbano I	Maggia	73					17	17				
	Verbano II	Maggia											
	Soazza	Mesolcina								17.395	25	70%	7.605
Isola	Spina (Isola)	Mesolcina	75	1.933	190	250	230	17.25	17.395				
Carmena	Morobbia	Morobbia	9					2	2	2	3	67%	1
Oberaar	Grimsel I (Oberarr)	Oberhasli	453		160	280	200	90.6	90.6	150.027	212	71%	61.973
Räterichsboden	Handeck II	Oberhasli	279		180	280	213	59.427	59.427				
	Handeck III	Oberhasli											
	Handeck I	Oberhasli											
	Innerkirchen I	Oberhasli											
	Hopflauenen	Oberhasli											
	usw.	Oberhasli											
	Clusanfe	Salanfe								42.09	59	71%	16.91
	Giétroz du Fond	Salanfe											
Salanfe	Miéville	Salanfe	230		150	250	183	42.09	42.09				
Sanetsch	Innergsteig	Sanetsch	37					9	9	9	12	75%	3
Schiffenen	Schiffenen	Schiffenen	185		250	250	250	46.25	46.25	46.25	65	71%	18.75
Contra	Gordola	Verzasca	660		200	250	233	153.78	153.78	153.78	217	71%	63.22
	Tenero	Verzasca											
Curnera	Sedrun	Vorderrhein	562	1.943	200	250	233	130.946	132.038	434.398	600	72%	165.602
Nalps	Sedrun	Vorderrhein	594	1.190	180	250	227	134.838	135.545				
Sta. Maria	Sedrun	Vorderrhein	654	0.836	200	270	242	158.268	158.815				
Runcahez	Tavanasa	Vorderrhein	33					8	8				
	Rothenbrunnen	Zervreila								147.893	230	64%	82.107
	Safien Platz	Zervreila											
Zervreila	Zervreila	Zervreila	626	6.069	200	280	219	137.094	140.893				
Egschi	Realta	Zervreila	30					7	7				
Summe			23037	241.4421429	7055	9135	8271	4849.152	4923.877	4696.592	7262		2565.408

Name of dam	Name of station	Name of group	Steel for tunnels	Steel for machines	Reinforcing steel	Steel total	Turbined water	Construction energy
			kg	kg	kg	kg	Mio. m3/a	GWh
Albigna	Bondo	Bergell					31	
		Bergell					170	
		Bergell						
		Bergell					27	
		Bergell					88	
		Bergell					26	
		Bergell						
		Bergell						
Gebidem	Bitsch (Biel	Bitsch					334	
Malvaglia	Biasca	Blenio					481	100
Carassina	Luzzone	Blenio					120	
Luzzone	Olivone	Blenio					212	
Molina	Sassello	Calancasca					102	
Les Toules	Orières	Drance d'E.					168	
	Pallazuit	Drance d'E.					87	
	Tsi	Drance d'E.						
Vieux Emosson	Châtelard-Barberine I+II	Emosson						
Emosson	Châtelard-Vallorcine	Emosson						
	La Bâtiaz	Emosson						
	usw.	Emosson						
Punt dal Gall	Ova spin	Engadin	5710000			5710000	320	
	Ova Spin-Dotierzentrale	Engadin					17	
Ova Spin	Pradella	Engadin					985	
	Punt dal Gall	Engadin					43	
Vasasca	Guimaglio	Guimaglio					43	
Göschenenreuss	Paffensprung	Göschenen						
	usw.	Göschenen						
	Chippis (Navisence)	Gougra					134	
Moiry	Mottec	Gougra					103	
Turtmann	Mottec	Gougra						
	Vissoie	Gougra					208	
	Vissoie	Gougra					4	
Cleuson	Chandoline	Grande Dixence						
Grande Dixence	Chandoline	Grande Dixence						
	Fionnay	Grande Dixence						
Mauvoisin	Fionnay	Grande Dixence						
	Bieudron	Grande Dixence						
	Nendaz	Grande Dixence						
	Chanrion	Grande Dixence						
	Riddes	Grande Dixence						
Z'Mutt	Z'Mutt	Grande Dixence						
	Cleuson	Grande Dixence						
	Stafel	Grande Dixence						
	Ferpercle	Grande Dixence						
	Arolla	Grande Dixence						
Roggiasca	Grono	Grono					74	
Rossens	Hauterive	Hauterive					1140	
Sufers	Bärenburg	Hinterrhein	2670000			2670000	754	
	Bärenburg	Hinterrhein					31	
Valle di Lei	Ferrera I	Hinterrhein					317	
	Ferrera II	Hinterrhein					31	
Bärenburg	Sils (KHR)	Hinterrhein					772	
Hongrin	Veytaux	Hongrin					113	
Châtelot	Le Châtelot	Le Châtelot					612	
Les Clées	Les Clées	Les Clées					325	
	Chamarin	Lienne					1	
Zeuzier	Croix	Lienne					78	
	St. Léonard	Lienne					97	
	Linthal (Limmern)	Linth-Limmern	1660000	3102000	4100000	8862000	220	88
	Tierfehd (Hintersand)	Linth-Limmern					71	
Limmern	Tierfehd (Limmern)	Linth-Limmern					122	
Lucendro	Airolo	Lucendro					48	
Sella	Airolo	Lucendro						
	Tremola/Sella	Lucendro						
Gries	Altstafel	Maggia					21	
Robiei	Bavona	Maggia					148	
Zöt	Bavona	Maggia						
	Cavergno	Maggia					378	
Sambuco	Peccia (Sambuco)	Maggia					110	
Cavagnoli	Robiei	Maggia					61	
Naret I+II	Robiei	Maggia						
Palagnedra	Verbano I	Maggia					845	
	Verbano II	Maggia					196	
	Soazza	Mesolcina					163	
Isola	Spina (Isola)	Mesolcina					70	
Carmena	Morobbia	Morobbia					57	
Oberaar	Grimsel I (Oberarr)	Oberhasli						
Räterichsboden	Handeck II	Oberhasli						
	Handeck III	Oberhasli						
	Handeck I	Oberhasli						
	Innerkirchen I	Oberhasli						
	Hopflauenen	Oberhasli						
	usw.	Oberhasli						
	Clusanfe	Salanfe	3000000			3000000		
	Giétroz du Fond	Salanfe						
Salanfe	Miéville	Salanfe					44	
Sanetsch	Innergsteig	Sanetsch					22	
Schiffenen	Schiffenen	Schiffenen					1481	
Contra	Gordola	Verzasca					434	
	Tenero	Verzasca					22	
Curnera	Sedrun	Vorderrhein	30000000	3100000	7000000	40100000		
Nalps	Sedrun	Vorderrhein						
Sta. Maria	Sedrun	Vorderrhein					215	
Runcahez	Tavanasa	Vorderrhein					538	
	Rothenbrunnen	Zervreila					241	
	Safien Platz	Zervreila					178	
Zervreila	Zervreila	Zervreila					138	
Egschi	Realta	Zervreila					36	
Summe			43040000	6202000	11100000	60342000	13907	188