Østfoldforskning

Memo SUSTAINABLE INNOVATION

No:	AR 02.15 Open memo
Keywords:	Hydropower, run of river, reservoir, LCA update
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Date:	February 19 2015 (based on AR 07.12 confidential report).

The inventory and life cycle data for Norwegian hydroelectricity

Background and aim

In 1998 Ostfold Research performed a comprehensive LCA study of electricity from 8 Norwegian hydropower stations, including the distribution net and losses by distribution on high and low voltage, respectively (Vold et al., 1998). Emissions from inundation of land were not included due to limited research. At that time, no PCR was available for hydroelectricity. In 2007 Ostfold Research updated completely the LCA for one of the studies (Trollheim) and in 2011 a lifetime adjustment was performed for the 7 other LCA's to be in line with the last version of the PCR for hydroelectricity (PCR 2007:08). In 2011 NVE made LCA's of electricity from 2 additional hydropower stations. The 10 hydropower stations represent 4.3% of the Norwegian hydropower production.

The aim of this study is thus to model the average Norwegian hydropower production based on LCI data from the 10 available LCA's and to include GHG emissions from inundation of land.

The original AR-report (AR 05.12) was made in June 2012. This updating is due to the following changes:

- An updated Trollheim EPD has been made (2012).
- One additional LCA has been included (EB Embretsfoss E4/run-of-river 1st life cycle), which means that 11 hydropower stations are now included, representing 4.5% of the Norwegian hydropower production.
- The inundation of land numbers have been updated (from 1.6 to 1.9 g CO2-eqv./kWh).

Methodology and assumptions

ISO 40040/44/48 is used for the LCA's of the electricity from the 11 hydropower stations. Other assumptions can be found in the respective, original, documents, summarised in table 1:

Table 1 Background documentation of the involved LCA studies

Power station	Original study made by	Reference
Rånåsfoss I	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Rånåsfoss II	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Suldal II	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
B	NVE	Sidelnikova (2011)
A	NVE	Sidelnikova (2011)
Embretsfoss E4	Ostfold Research	Arnøy (2013b) EPD Norge (2013b)
Såheim	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Kvanndal	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Trollheim	Ostfold Research	Arnøy (2013a) EPD Norge (2013a)
Gråsjø	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Svartisen	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)

Some corrections and updates have been made of the original studies. A summary of this is found in table 2.

Table 2 Corrections and updates

<table>
<tr><th>Power station</th><th>Changes made</th><th>Date/responsible</th></tr>
<tr><td>Rånåsfoss I</td><td rowspan="3">- Transferral of the original LCI dataset from the old software tool to SimaPro via CSV files and excel.
- Inclusion of parameters for lifetime settings.
- Lifetime adjustment for dam and tunnel (from 60 to 100 years).
- Inclusion of 1 kWh intrinsic energy per kWh produced hydroelectricity.
- Inclusion of specific losses in tunnel, turbine and generator.
- Inclusion of land use data (transformation into industrial area).</td><td rowspan="3">July 2011, Silje Arnøy and Kaja H. Engebrigtsen (summer students, Ostfold Research), documented in AR 04.11.</td></tr>
<tr><td>Rånåsfoss II</td></tr>
<tr><td>Suldal II</td></tr>
<tr><td>B (NVE)</td><td rowspan="2">No changes, only transferral of of dataset from NVE to Ostfold Research (S-processes in CSV-files).</td><td rowspan="2">November 2010, Ingunn Saur Modahl.</td></tr>
<tr><td>A (NVE)</td></tr>
<tr><td>Embretsfoss E4</td><td>New dataset 2012.</td><td>December 2012, Silje Arnøy/Ingunn Saur Modahl.</td></tr>
<tr><td>Såheim</td><td>See notes for Rånåsfoss I, Rånåsfoss II and Suldal II.</td><td rowspan="2">See notes for Rånåsfoss I, Rånåsfoss II and Suldal II (above).</td></tr>
<tr><td>Kvanndal</td><td>See notes for Rånåsfoss I, Rånåsfoss II and Suldal II. In addition:</td></tr>
</table>

	- Correction of the dataset for 'mining underground' in the 'tunnel' activity. - Updated numbers for emissions from inundation of land.	Ingunn Saur Modahl, December 2012.
Trollheim	The results from the updated EPD (December 2012) have been included.	December 2012, Ingunn Saur Modahl.
Gråsjø Svartisen	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II. In addition: - Updated numbers for emissions from inundation of land.	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II (above). Ingunn Saur Modahl, December 2012.

In Vold et al. (1998) the weighting of the 8 (at that time) power stations were based on a detailed categorisation of Norwegian hydropower stations into the following groups: small hydro, high head/annual reservoir, high head/multi-season reservoir, medium head, run-of-river, medium head/older than 60 years and run-of-river/older than 60 years. Recent work by Raadal and Modahl (2010) concludes that the variations within the different stations are too small for making it reasonable to categorise Norwegian hydropower according to different physical parameters and related GHG emissions. Hence, in this study, the weighting is based on only four categories power plants; run of river (1st and 2nd life cycle) and reservoir (1st and 2nd life cycle).

The power stations in the 11 LCA studies available thus represent their specific category in accordance with their annual production. The NVE (Norwegian Water Resources and Energy Directorate) database of hydroelectricity production (NVE, 2010) has been used for this purpose. The Norwegian annual average hydroelectricity production volumes for the chosen categories are shown in table 3.

Table 3 Annual average production volume for Norwegian hydropower stations#

Category*		**Annual average production volume (GWh/year)**	**Share of the total production volume**
Run of river	2nd life cycle	302	0,2 %
	1st life cycle	29 113	23,8 %
Reservoir	2nd life cycle	329	0,3 %
	1st life cycle	92 559	75,7 %

* The NVE database do not include information regarding if the power stations are defined as 1st or 2nd life cycle. Hence we have used the commissioning year as an indication (power stations older than 100 years are defined as 2nd life cycle).

\# The 2010 dataset from NVE has been used for determining the different categorie's share of the annual production even if some changes have occurred regarding production volume (increased production due to Embretsfoss and updated annual production at Trollheim). These changes are regarded as small.

In table 4 each of the 11 studied hydropower stations' representative share in the modelling of the Norwegian hydropower are shown.

Table 4 The power stations' representative share in the modelling of Norwegian hydropower

Category[1]		Power station data[2]			Representative share			
Type of regulation	**Life cycle**	**Name of power station**	**Comis-sioning year**	**Mean annual production (GWh)**	**Share within each category**	**Share of the total production volume**	**Share of the total production volume**	**Comments**
Run of river	2nd	Rånåsfoss I	1921	230	100 %	0.2 %	0.2 %	Annual production from Vold et al. (1998). Defined as 2nd life cycle due to a lifetime > 60 years (Vold et al., 1998).
Run of river	1st	Rånåsfoss II	1983	271	20 %	23.8 %	4.8 %	Annual production from Vold et al. (1998).
		Suldal II	1967	751	54 %		12.9 %	
		B (NVE)	2004	13	1 %		0.2 %	Power station 'B' in Sidelnikova (2011).
		A (NVE)	2007	62	4 %		1.0 %	Power station 'A' in Sidelnikova (2011).
		Embretsfoss E4	2012	286	21%		5.0%	New hydropower station 2012, documented in Arnøy (2012b) and EPD Norge (2012b).
Reservoir	2nd	Såheim	1915	841	100 %	0.3 %	0,3 %	Defined as run of river in the NVE database due to non-adjustable water flow. In Vold et al. (1998) defined as reservoir due to reservoir connection.
Reservoir	1st	Kvanndal	1967	182	6 %	75.7 %	4.5 %	
		Trollheim	1968	849	27 %		20.4 %	
		Gråsjø	1970	65	2 %		1.5 %	
		Svartisen	1993	1 996	65 %		49.2 %	
Total (representative group)				5 546			100,0 %	
Total production volume (Norway)				122 302				
The representative group of power stations' share of the total production volume				4.5 %				

1) Defined by Vold et al., (1998).
2) Data from NVE unless otherwise commented.

Inundation of land is included for all the reservoir power stations. Studies by Sintef Energy Research based on measurements in Follsjø (connected to Trollheim power station), net flux calculation and production volume of Trollheim power station have lead to the resulting average inundation value of 1.9 g CO_2-eq./kWh for this reservoir and production volume (Harby, Brakstad and Sundt, 2006). The net emission is based on net diffusive emissions of both CO_2 (0.989 Gg/year) and CH_4 (0.028 Gg/year, assumed as biological). This is as update from June 2012, when the net emission was based on emissions of C as CO_2 only. These values can vary depending on several factors. However, it is the best estimate available for Norwegian conditions, and is thus used for all the reservoir power stations in this study.

Results

In figure 1 the GWP is shown as an LCA network. Cut off is used to make the figure readable, hence not all processes are shown.

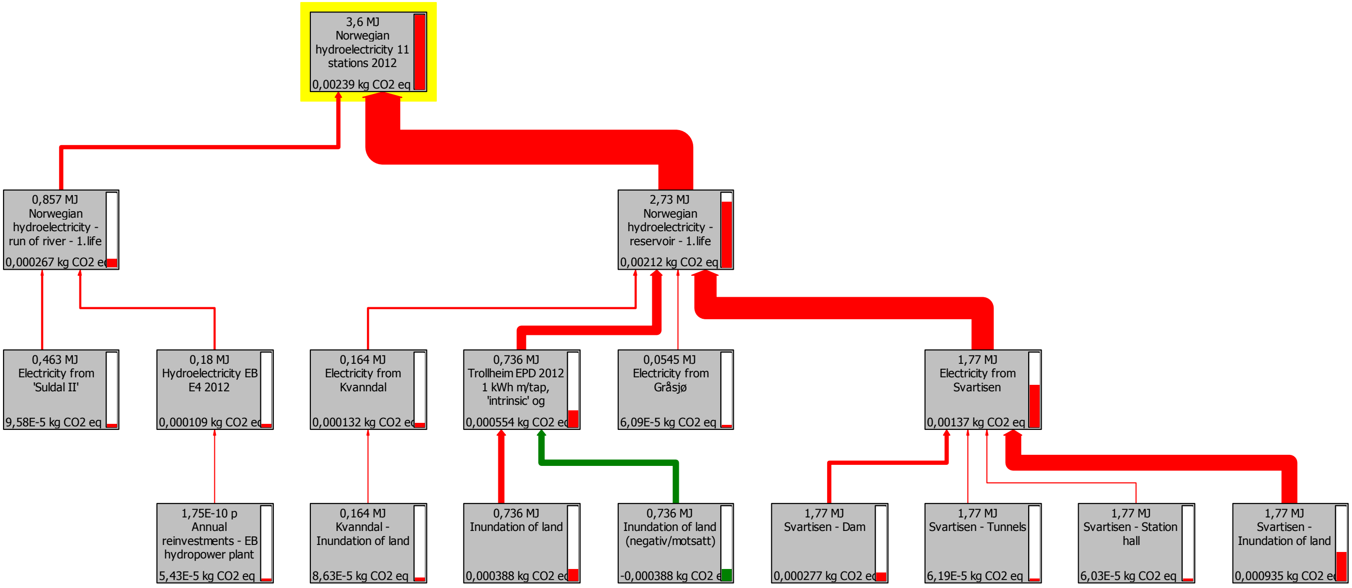

Figure 1 ***Global warming potential, shown as an LCA network, for Norwegian hydroelectricity. 2% cut off is used to make the figure readable (the system consists of 2285 nodes).***

In figure 2 the contribution into inundation of land and infrastructure/maintenance/daily use is shown. Due to the aggregated data for the power stations A and B made by NVE, it was not possible to split the results further.

![Østfoldforskning]

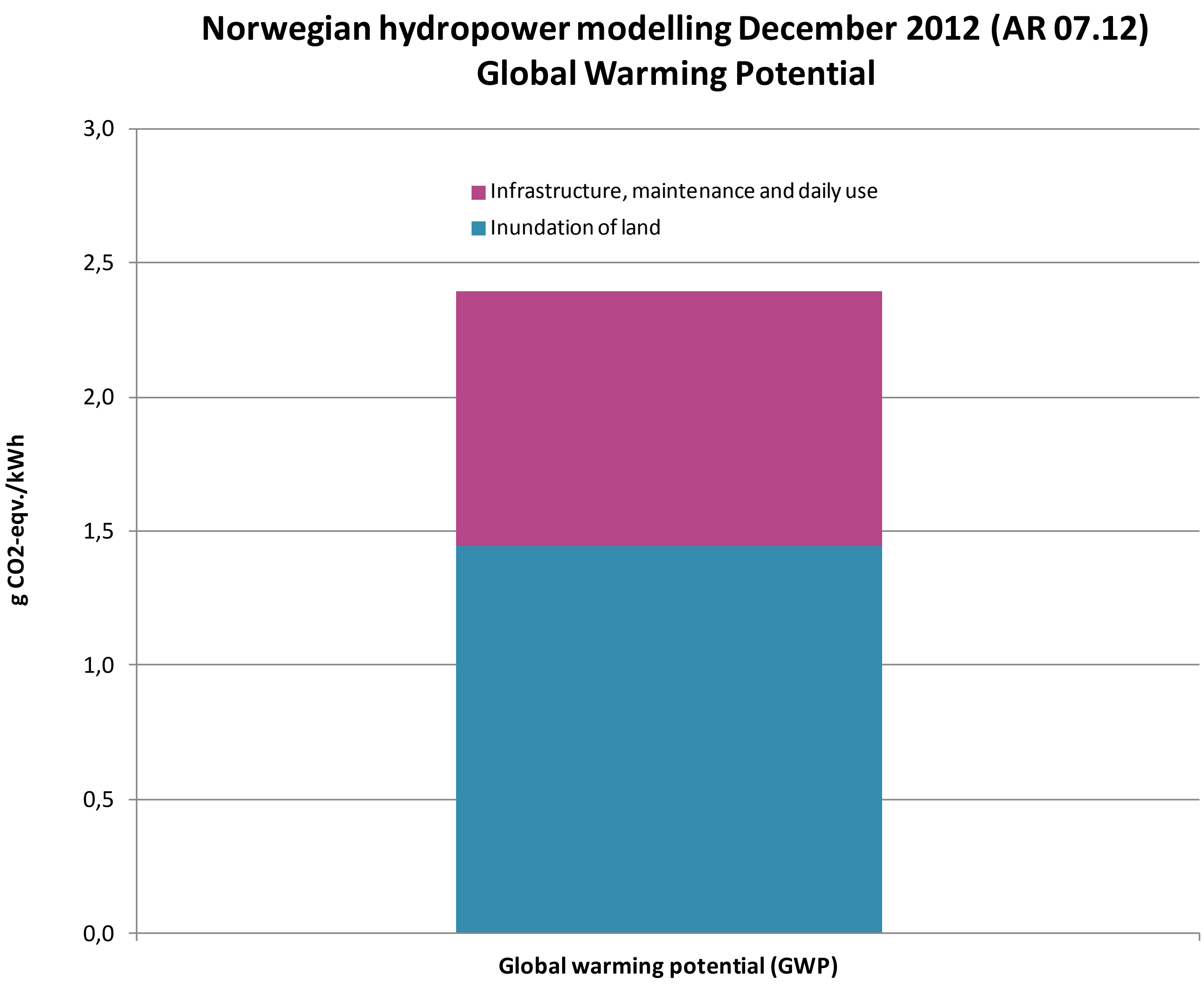

Figure 2 ***The global warming potential for Norwegian hydropower, split into inundation of land and infrastructure/maintenance/daily use.***

In table 5 the results for all the analysed impact categories are shown.

Table 5 ***Results from the modelling of Norwegian hydropower***

Environmental impact category	Unit	Norwegian hydropower (total)	Inundation of land	Infrastructure, maintenance and daily use
Global warming potential (GWP)	g CO_2-eqv./kWh	2.39	1.44	0.95
Acidification potential	g SO_2-eqv./kWh	0.0067	-	0.0067
Eutrophication potential	g PO_4^{3-}-eqv./kWh	0.0017	-	0.0017
Photochemical ozone creation potential (POCP)	g C_2H_2-eqv./kWh	0.00067	-	0.00067
Ozone depletion potential (ODP)	g CFC-11-eqv./kWh	0.00	-	0.00
Cumulative energy demand (CED)	MJ LHV	3.90	-	3.90

Comment to the results:
Inundation of land has increased 0.22 g CO2-eqv./kWh from 1.22 g CO2-eqv./kWh to 1.44 g CO2-eqv./kWh due to the updated value (from 1.6 to 1.9 g CO2-eqv./kWh for reservoir power stations). The infrastructure/operation numbers have also increased (+0.11 g CO2-eqv./kWh), from 0.84 g CO2-eqv./kWh to 0.95 g CO2-eqv./kWh. This is mainly (+0.07 g CO2-eqv./kWh) due to the inclusion of Embretsfoss E4 in the run-of-river 1st life cycle category, which increase the average infrastructure/operation results in that category. The updating of Trollheim has also played a role (+0.02 g CO2-eqv./kWh).

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