Østfoldforskning

Memo	SUSTAINABLE INNOVATION
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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 represented 4,3 % of the Norwegian hydropower production (NVE, 2010).

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

The original AR-report (AR 05.12/AR 07.12) was made in June/December 2012 and April 2013, being later updated in February 2015 (AR 02.15) due to the following changes:

- An updated Trollheim EPD had been made (2012).
- One additional LCA had been made (EB Embretsfoss E4/run-of-river 1st life cycle), which meant that 11 hydropower stations were included in 2015, representing 4,5 % of the Norwegian hydropower production (NVE, 2010).

- The inundation of land numbers had been updated (from 1,6 to 1,9 g CO_2-eq./kWh) according to Harby, Brakstad and Sundt (2006).

This version considers the following changes:

- The Trollheim EPD has been updated once more (Callewaert, November 2018 and EPD Norge 2018). Emissions of COD have also been included. The calculation of COD emissions has been based on the method described in the PCR, i.e., amount of CO_2 released multiplied by (12/44) x 2,67.
- The inundation of land numbers for Trollheim and Gråsjø hydropower stations have been updated. This is included in the EPD for Trollheim, but has also been updated for electricity from the Gråsjø power plant:
  - Observations per area (CO_2 = 1,52 ton/ha, CH_4 = 0,043 ton/ha, assumed to be the same for Gråsjø and Follsjø lakes) are multiplied with the flood surface for Gråsjø (1050 ha) to get the yearly CO_2 and CH_4 emissions for Gråsjø lake. Thereafter, these emissions are summed with the annual inundation emissions for Follsjø lake (CO_2: 0,989 Gg/year and CH_4: 0,028 Gg/year) and divided by the annual electricity production of Trollheim and Gråsjø power plants.
  - In this way, electricity from Follsjø lake/Trollheim power plant and Gråsjø have the same inundation emissions per kWh produced.
- Electricity from Skjerka (Skjerka/reservoir 1st life cycle) hydro power plant has been added after an EPD was made in 2016 (Soldal, May 2015 and EPD Norge 2016).

Now 12 hydropower stations are included in the analysis, representing 5,0 % of the Norwegian hydropower production (NVE, 2010).

Methodology and assumptions

ISO 40040/44/48 is used to perform the LCA's of the electricity generated from the 12 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	Vold et al. (1998), later updated by: Arnøy (2013a) EPD Norge (2013a), later updated once more by: Callewaert (2018) EPD Norge (2018)
Gråsjø	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Svartisen	Stiftelsen Østfoldforskning STØ (now Ostfold Research)	Vold et al. (1998)
Skjerka	Ostfold Research	Soldal (2016) EPD Norge (2016)

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

Power station	Changes made	Date/responsible
Rånåsfoss I Rånåsfoss II Suldal II	- 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)	July 2011, Silje Arnøy and Kaja H Engebrigtsen (summer students, Ostfold Research), documented in AR 04.11
B (NVE) A (NVE)	No changes, only transferral of dataset from NVE to Ostfold Research (S-processes in CSV-files)	November 2010, Ingunn Saur Modahl
Embretsfoss E4	New dataset 2012	December 2012, Silje Arnøy/Ingunn Saur Modahl
Såheim	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II. Old calculation method for inundation of land.	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II (above) Ingunn Saur Modahl, December 2012
Kvanndal	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II. In addition: - Correction of the dataset for 'mining underground' in the 'tunnel' activity - Updated numbers for emissions from inundation of land in December 2012 (consider updating this calculation method next time).	
Trollheim	The results from the updated EPD (November 2018) have been included. New calculation method for inundation.	Mafalda Silva, April 2019
Gråsjø	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II. In addition: - Updated numbers for emissions from inundation of land in April 2019	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II (above) Inundation of land updated by Mafalda Silva, April 2019

Svartisen	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II. In addition: - Updated numbers for emissions from inundation of land in December 2012 (consider updating this calculation method next time).	See notes for Rånåsfoss I, Rånåsfoss II and Suldal II (above) Ingunn Saur Modahl, December 2012
Skjerka	New dataset included (old calculation method for inundation of land, consider updating this calculation method next time).	Mafalda Silva, April 2019

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 12 LCA studies available thus represent their specific category in accordance with their annual production. The Norwegian Water Resources and Energy Directorate (NVE) database of hydroelectricity production has been used for this purpose (NVE, 2010). 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[1]

Category[2]		**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 %

[1] 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).

[2] The 2010 dataset from NVE has been used for determining the different categories' share of the annual production even if some changes have occurred regarding production volume (increased production due to Embretsfoss, updated annual production at Trollheim and Skjerka). 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			Comments
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	
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	1921	286	21%		5,0%	New hydropower station 2012, documented in Arnøy (2013b) and EPD Norge (2013b)
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	5 %	75,7 %	3,8 %	Annual production from NVE (2010).
		Trollheim	1968	722	20 %		15,0 %	The previous mean annual production was 849 GWh, for the reference period 2007-2011. The used reference period in the updated EPD was 2013-2017.
		Gråsjø	1970	65	2 %		1,3 %	
		Svartisen	1993	1 996	55 %		41,4 %	Commissioning year changed from 1993 to 1995. NVE (2010).
		Skjerka	1997 (1932)	689	19 %		14,3 %	Commissioning year and mean annual production from Soldal (2016). The old power plant was built as early as 1932 (demolished).
Total (representative group)				6 180			100,0 %	
Total production volume (Norway)				122 333				
The representative group of power stations' share of the total production volume				5,0 %				

[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. The calculation of CO_2, CH_4 and COD emissions associated with inundation of land for both Trollheim and Gråsjø power stations, was previously described. For the remaining power stations, an average inundation value of 1,9 g CO_2-eq./kWh is used based on studies and measurements in Follsjø lake (connected to Trollheim powerplant) performed by SINTEF Energy Research (Harby, Brakstad and Sundt, 2006), and calculation based on annual emissions for Follsjø lake divided by the electricity production of Trollheim. Hence, the inundation numbers for Såheim, Kvanndal, Svartisen and Skjerka are NOT

based on annual emissions per area lake, as for Gråsjø and Trollheim. For the next update, one should consider updating the inundation numbers for Såheim, Kvanndal, Svartisen and Skjerka as well.

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.

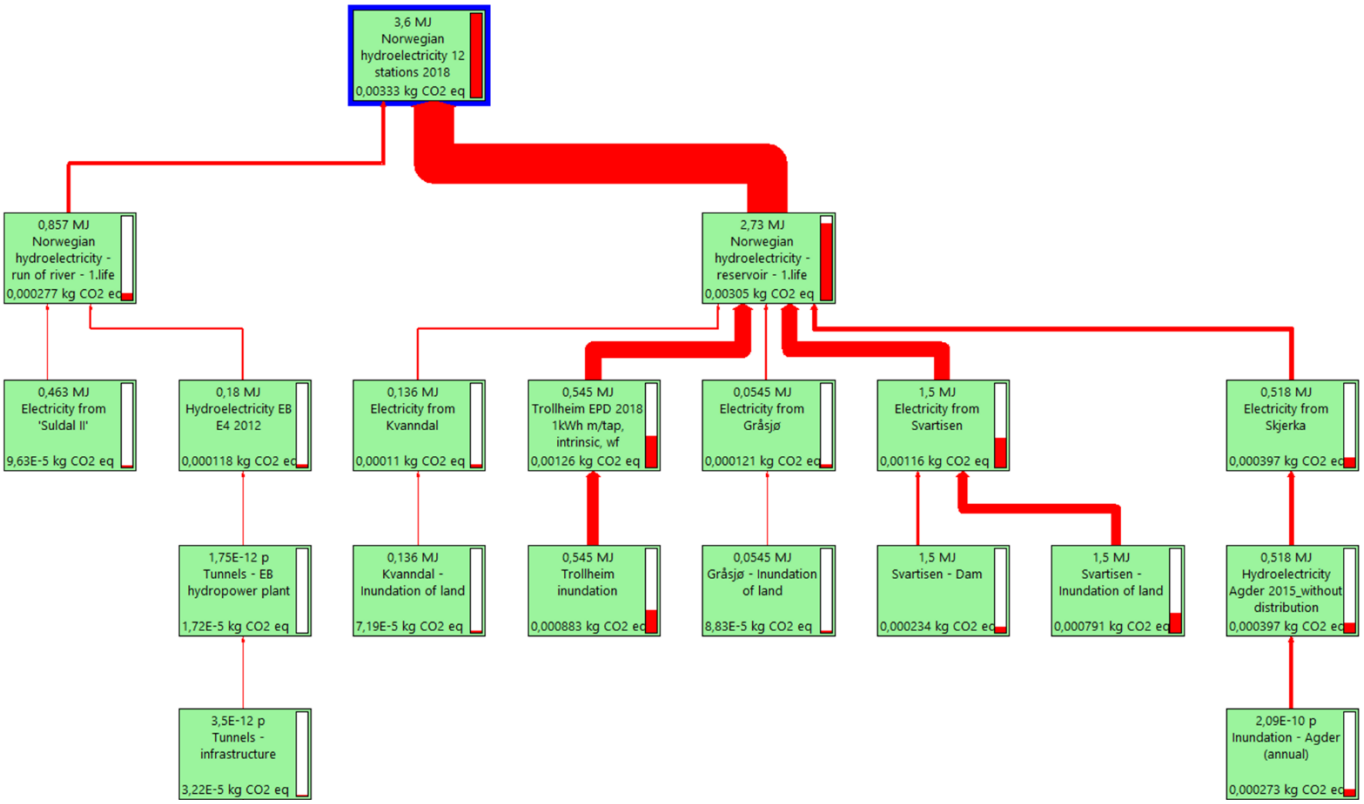

Figure 1 Global warming potential, shown as an LCA network, for Norwegian hydroelectricity. 2% cut off is used to make the figure readable.

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.

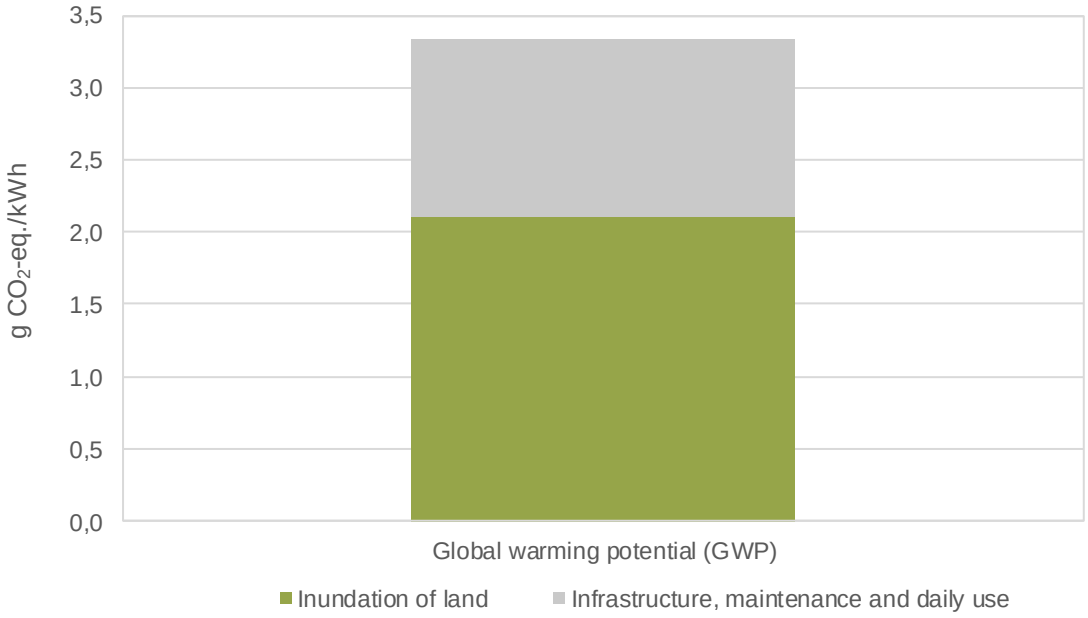

Figure 2 The global warming potential for Norwegian hydropower, split into inundation of land and infrastructure/maintenance/daily use.

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-eq./kWh	3,33	2,11	1,22
Acidification potential	g SO_2-eq./kWh	0,0152	-	0,0152
Eutrophication potential	g PO_4^{3-}-eq./kWh	0,0192	0,00355	0,0157
Photochemical ozone creation potential (POCP)	g C_2H_4-eq./kWh	0,000686	0,00000840	0,000677
Ozone depletion potential (ODP)	g CFC-11-eq./kWh	0,00	-	0,00
Cumulative energy demand (CED)	MJ LHV	6,11	-	6,11

Comment to the results:
Inundation of land has increased by 0,67 g CO_2-eq./kWh from 1,44 g CO2-eq./kWh to 2,11 g CO_2-eq./kWh[1] due to the updated values for Trollheim and Gråsjø, and to the inclusion of Skjerka in the reservoir 1st life cycle category. The infrastructure/operation numbers have also increased (+0.27 g CO2-eq./kWh), from 0,95 g CO_2-eq./kWh to 1,22 g CO_2-eq./kWh. This is mainly due to the updating of Trollheim but the inclusion of Skjerka in the reservoir 1st life cycle category also played a role in the increase of the average infrastructure/operation results in that category.

[1] The specific inundation results for Trollheim and Gråsjø power plants are 5.83 g CO2-eq./kWh, and for the five reservoir 1st life cycle power plants the mean value is 2.78 g CO2-eq./kWh.

The result's calculating file can be found here: O:\FM\Energihandel og miljø 2020_1288\05 Analyser og tolkning\Hydropower Norwegian (file name 'Norwegian hydropower 2018 incl inundation – figures').

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For internal use:

Excel file with exported data: O:\FM\Energihandel og miljø 2020_1288\05 Analyser og tolkning\Hydropower Norwegian\Norwegian hydropower 2018 incl inundation - figures.xlsx