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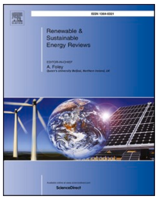

Improving the accuracy of electricity carbon footprint: Estimation of hydroelectric reservoir greenhouse gas emissions

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ABSTRACT

Hydropower is usually considered as a low-carbon electricity source, as it does not lead to direct greenhouse gas (GHG) emissions, unlike producing electricity from fossil fuels. However, the flooding of lands following the construction of the dam generally leads to an increase in biogenic GHG emissions due to the degradation of biomass found in the newly created reservoir. The life cycle assessment (LCA) methodology is widely used to calculate and compare the carbon footprint of different electricity production pathways, while considering all life cycle stages. Net biogenic GHG emissions from hydropower reservoirs have been poorly considered in LCA because of the scarcity of data. These emissions are complex to quantify as several mechanisms are involved, and extrapolating observations from one reservoir to another is risky as emissions vary greatly depending on different parameters, such as climate, geographic location, age of impoundment, and watershed properties. The objective of this article is to compare different approaches to estimate hydropower reservoir emissions in LCA, to select the most appropriate one, and to apply it to the calculation of the carbon footprint of electricity distributed in the Canadian province of Québec. Net biogenic GHG emissions of all hydropower reservoirs in the province (with 2.5 and 97.5% confidence intervals), as estimated using the G-res model, are 16.5 (14.7–18.6) $gCO_2 \cdot kWh^{-1}$ and 0.29 (0.23–0.35) $gCH_4 \cdot kWh^{-1}$. Combined to ecoinvent data for other life cycle emissions, the carbon footprint of electricity distributed in the province in 2017 is 34.5 $gCO_2eq \cdot kWh^{-1}$.

1. Introduction

Electricity and heat production were responsible for 30% of the world's anthropogenic greenhouse gas (GHG) emissions in 2016, mainly due to fossil fuel combustion [1]. Producing electricity from low-carbon energy sources is thus seen as a solution having a high climate change mitigation potential. For instance, life cycle GHG emissions for wind, hydropower, concentrating solar power, and solar photovoltaics range between 5 and 50 $gCO_2eq \cdot kWh^{-1}$ according to a review study performed by the National Renewable Energy Laboratory, while they range from 480 to 1000 $gCO_2eq \cdot kWh^{-1}$ for thermal natural gas, oil, and coal [2]. Hydropower is currently the largest source of renewable energy and is a low-carbon electricity source. It contributed to 16.4% of the world's electricity production in 2017, and a steady growth is projected in the future [3,4]. Hydroelectricity is produced from the energy of flowing water, which does not lead to direct GHG emissions, unlike producing electricity from fossil fuel combustion. Although, when dam construction causes the flooding of land, the overall carbon balance will be affected, generally resulting in net biogenic carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions from the degradation of biomass found in these newly created reservoirs [5–7]. To estimate biogenic GHG emissions associated with hydroelectricity production, reliable measurements of CO_2, CH_4 and N_2O emissions from reservoirs over space and time are needed, as well as robust estimates of carbon sinks and sources from the terrestrial and aquatic ecosystems prior to flooding [7]. Net biogenic carbon emissions (commonly called Net GHG Emissions) to be attributed to hydroelectricity production are estimated by the difference between pre- and post-impoundment carbon fluxes, representing respectively the emissions of the landscape before impoundment and the new emissions associated with the reservoir [8].

Several mechanisms are involved in the carbon cycle of freshwater ecosystems. Indeed, freshwater ecosystems receive carbon from terrestrial ecosystems through drainage, sequester carbon through primary production, bury carbon in sediments, emit carbon from biomass degradation and respiration, and transport carbon downstream up to

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List of abbreviations

CH_4	Methane
CIRAIG	International Reference Centre for the Life Cycle of Products, Processes and Services
CO_2	Carbon dioxide
d	day
g	gram
GHG	Greenhouse gas
GWh	gigawatt hour
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
km^2	square kilometer
kWh	kilowatt hour
LCA	Life cycle assessment
m^2	square meter
mg	milligram
mol	mole
MW	megawatt
N_2O	Nitrous oxide
PCR	Product category rule
SETAC	Society of Environmental Toxicology and Chemistry
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
yr	year

oceans [9,10]. Human activities in the land surrounding the reservoir may also result in additional GHG emissions from freshwater ecosystems through sewage and agricultural pollution [11]. Dams can affect the natural carbon cycle of freshwater ecosystems through the flooding of terrestrial vegetation and soils, which could result into additional carbon emissions, especially during the early years following the creation of the reservoir. Over time, flooded organic matter will slowly decompose according to local conditions, and emissions will tend to decrease [8,12]. The impoundment may also increase sedimentation and decay in reservoirs due to longer water residence times, potentially leading to higher CO_2 and CH_4 emissions [13]. However not yet fully documented and rarely included in studies, the change in hydrology regime will also displace where the carbon is processed, leading to high emissions observed in the reservoir that would have occurred anyway further down the water continuum [8]. N_2O is another greenhouse gas that can be emitted from reservoirs. However, studies have shown no difference in terms of N_2O emissions for boreal reservoirs compared to natural aquatic ecosystems [11,12,14]; they will therefore be excluded from this study. Moreover, the Intergovernmental Panel on Climate Change (IPCC) considers that large sources of nitrogen are related to human activities taking place in the watershed upstream of the reservoir. Therefore, to avoid double counting, they are not considered for hydropower reservoirs.

Ideally, the estimation of pre- and post-impoundment GHG emissions would consider all these mechanisms occurring in the reservoir, as well as downstream. As these emissions have strong spatial and temporal variability, which makes measurement challenging [8,12,15,16], an international project has been conducted to provide consensual guidelines to help scientists estimating net GHG emissions from reservoirs in a standardized and robust way [17]. Different types of GHG fluxes must be estimated or measured according to these guidelines: 1) bubbling (ebullition) emissions, 2) diffusive emissions from the reservoir water surface, 3) diffusion through aquatic plant stems, 4) degassing at the reservoir outlet (immediately after water passes through turbines), and 5) diffusive emissions further downstream. Depending on the location (e.g. climate) and characteristics of the reservoir (e.g. depth, vegetation cover), these types of emission can be more or less important. For instance, diffusion through aquatic plant stems is not really observed in reservoirs located in the province of Québec as most of their shorelines are eroded by the combined action of wave and wind to mineral horizon and bed rock [12].

Bubbling emissions come mainly from CH_4 accumulating in sediments following anaerobic degradation, and usually occur in shallow parts of the reservoirs where the hydrostatic pressure is lower [8,12,15]. Bubbling emissions are intermittent and more important in warm waters [18] containing high levels of organic matter [15]. They can be quantified using different techniques, such as inverted-funnel method or acoustic techniques [17,19]. Diffusive CO_2 and CH_4 fluxes at the reservoir water surface can be quantified using surface floating chambers, or calculated based on the partial pressure gradient and using the thin boundary layer diffusive process model [8,12,16,20]. Degassing emissions are caused by the important pressure change at the outlet of turbines and spillways. They can be quantified using gas concentrations directly upstream and downstream the dam [17]. Downstream diffusive fluxes are more difficult to quantify because of currents and rapid flowing waters, as opposed to reservoirs. The main technique used consists in calculating these fluxes based on measurements of gas concentrations [8,12,16,20]. Finally, pre-impoundment fluxes from the terrestrial ecosystem can be measured using chambers, soil core sampling, or eddy covariance towers [7,21].

The life cycle assessment (LCA) methodology [22,23] is widely used to calculate the carbon footprint of different electricity production pathways, while considering all life cycle stages, such as construction of infrastructures, fuel production, or electricity generation. Life cycle carbon footprint results can be used to compare the climate change impacts associated with different electricity sources. They can also be integrated in other LCA studies in which electricity is consumed. As electricity is part of most products' life cycle, the reliability of electricity carbon footprint will inadvertently affect the reliability of most LCA results, and of any decisions made on their basis.

Biogenic GHG emissions from hydropower reservoirs have been poorly considered for a long time in LCA because of the scarcity of data [11,24]. Moreover, it is difficult to extrapolate observations from one reservoir to another since emissions of biogenic CO_2 and CH_4 vary greatly among them, depending on different parameters, such as climate, geographic location, age of impoundment, and watershed properties [6,7,12,25]. Published reviews of LCA studies on hydropower plants have shown great variability in results, from 0.2 to 152 $gCO_2eq \cdot kWh^{-1}$ for [26], and from 1.2 to 3000 $gCO_2eq \cdot kWh^{-1}$ for the more recent [24], mainly due to biogenic reservoir emissions. LCA studies that included these emissions usually estimated only gross emissions (i.e. post-impoundment only) as pre-impoundment data were not available [27]. For instance, pre-impoundment emissions have been found for two hydroelectric reservoirs only, i.e. the Eastmain-1 reservoir in the province of Québec [7], and the Three Gorges reservoir in China [28]. Recent studies have addressed this issue and proposed emission factors to quantify biogenic GHG emissions from hydropower reservoirs in LCA [29,30]. In addition to its contribution to academic research projects, Hydro-Québec, the public utility that manages electricity generation, transmission and distribution in the province, has carried out several field measurements in the past. However, quantification of reservoir emissions is still challenging, as results vary substantially from reservoir to reservoir and need to be better documented. Recently, the G-res model has been developed by the International Hydropower Association and the UNESCO Chair in Global Environmental Change in order to more accurately estimate GHG emissions from hydropower reservoirs [31].

The objective of this article is to compare different approaches to estimate hydropower reservoir emissions in LCA, to perform a critical analysis in order to select the most appropriate one, and to apply the selected approach to the LCA of hydroelectricity production in the Canadian province of Québec in order to calculate the carbon footprint of the electricity mix distributed in the province.

2. Material and methods

2.1. Overview of electricity produced and distributed in Québec

In 2017, hydropower represented 99.8% of the total amount of electricity produced by Hydro-Québec, relying on 63 power plants for a total installed capacity of 36,767 MW [32]. From this installed capacity, 62.4% (22,959 MW) was composed of 20 reservoir-type power plants, while the remaining 37.6% was composed of 43 run-of-the-river-type power plants. The composition of electricity mix distributed in the province is slightly different because of electricity purchase from local producers, as well as imports and exports. In 2017, as shown in Table 1, 94.47% of distributed electricity was from hydropower, while 0.04% was from thermal, 0.18% from nuclear, and 5.31% from other renewable sources [33].

Run-of-the-river power plants are defined as power stations fed directly by a river. They have little to no storage capacity, meaning that their generating output entirely depends on the flow of the river. However, some of the run-of-the river-type power plants might have small associated flooded lands. Table A1 in appendix presents a detailed list of reservoir and run-of-the-river with flooded lands hydropower plants in Québec, while Table A2 presents run-of-the-river hydropower plants without any flooded lands. In addition, Hydro-Québec's hydropower fleet also includes reservoirs (included in Table A1) and other flooded lands that are not directly associated with a power plant (Table A3 in appendix). As an example, Rupert downstream and upstream diversion bays have been created to divert part of the Rupert's flow toward the Eastmain reservoir.

For each approach presented in section 2.2, reservoir CO_2 and CH_4 emissions were calculated in $g \cdot kWh^{-1}$ for two different bases: i) per kWh of electricity produced by reservoir and run-of-the-river with flooded lands power plants (first column in Table 5), and ii) per kWh of electricity produced by all hydropower plants (second column in Table 5). For the first case, the denominator is the sum of annual electricity production for all the reservoir and run-of-the-river with flooded lands power plants (Table A.1, 1.42×10^{11} $kWh \cdot yr^{-1}$). For the second case, it is the total annual hydroelectricity production from all hydropower plants owned by Hydro-Québec (Table A1 and Table A.2, 1.78×10^{11} $kWh \cdot yr^{-1}$). The values of annual electricity production are averages over a 5-year period, i.e. from 2011 to 2015 inclusive, except for three power plants that became operational after 2011 (see Table A1).

Table 1
Composition of the electricity mix distributed in the province of Québec in 2017 [33].

Source	Composition (%)
Hydropower generated in Québec	79.99%
Hydropower bought from Churchill Falls in Newfoundland and Labrador	11.93%
Hydropower bought from other regions	2.55%
Thermal (coal and fuel oil)	0.01%
Thermal (natural gas)	0.03%
Nuclear	0.18%
Wind	4.38%
Thermal (Biomass)	0.87%
Thermal (Biogas, waste) and solar	0.06%

2.2. Comparison of different approaches to estimate reservoir emissions

The state-of-the-art approach to estimate reservoir emissions is to calculate the cumulative net emission over 100 years, which is considered as a good estimate for the lifetime of a reservoir [34–36]. The net emission is the difference between post-impoundment emissions (from bubbling, diffusion at the reservoir surface, degassing, and downstream diffusion) and pre-impoundment emissions. The study on Eastmain-1 reservoir (Québec, Canada) is the only one that has integrated all emission pathways to estimate the net GHG emission [7]. A similar approach is actually taking place at the Romaine complex (Québec, Canada) and the results should be available by 2020–2021. There is a clear need to assess more reservoirs using this approach, as explained in section 3.

However, this approach can rarely be fully applied because of missing data. For instance, pre-impoundment measurements are rarely available, as no measures have been taken prior to impoundment. Data are also often lacking for some types of post-impoundment emissions, such as downstream diffusive emissions, because they are difficult to measure. Another issue is that some natural emissions that were occurring downstream from the dam prior to impoundment might now be observed at the reservoir surface as the residence time in the reservoir has considerably increased [8]. If those natural displaced emissions are ignored because of missing data, there is a risk of overestimating GHG emissions caused by the creation of the dam. One solution often proposed to overcome this issue is to calculate emissions over 10 years, assuming that after this period, emissions are all from natural processes, so that the net emission would be zero. A new approach proposes to use predicted emissions at 100 years as the natural baseline emissions, and to remove them from the post-impoundment emissions [8]. When pre-impoundment emissions are not available, gross emissions (i.e. only post-impoundment emissions) for a period of 10 years could be used as a proxy in the absence of alternatives. The net emission obtained is then divided by total electricity generation over the lifetime to get GHG emissions per kWh of electricity produced.

2.2.1. Gross emissions (10 and 100 years) based on a set of historic measurements

Average CO_2 emissions per kWh, based on a 10-year gross emissions approach, were calculated using Equation (1), as inspired from the 2006 IPCC guidelines, volume 4 (Agriculture, Forestry and Other Land Use), Appendix 2, Equation 2A.1 [37]. Average CO_2 daily diffusive emissions come from historical data, as estimated from more than 11,000 measurements on 24 reservoirs and natural water bodies over the past decades by Hydro-Québec (Table 2). The total reservoir area is the sum of average areas for all water bodies included in Tables A1 and A3 (1.93×10^{10} m^2). As a sensitivity analysis, gross emissions were also calculated using the sum of minimum and maximum reservoir areas (instead of average) for water bodies in Table A1. For these cases, total reservoir areas were 1.60×10^{10} m^2 and 2.26×10^{10} m^2 respectively, and results of this sensitivity analysis are shown in parenthesis in Table 5.

$$E_{gross\ 10\ IPCC} = \frac{P\ \times\ 10yr\ \times\ E_{diff}{}^{1-10}\ \times\ A}{Prod\ \times\ LT} \times 10^{-3} \tag{1}$$

where $E_{gross\ 10\ IPCC}$ = average emissions per kWh [$gCO_2 \cdot kWh^{-1}$]

P = average number of days without ice cover [180 $d \cdot yr^{-1}$]
$E_{diff}{}^{1\text{-}10}$ = average daily diffusive emission for days without ice cover for the first 10 years after flooding [$mgCO_2 \cdot m^{-2} \cdot d^{-1}$]
A = total average (or minimum/maximum) reservoir area [m^2]
$Prod$ = total annual electricity production [$kWh \cdot yr^{-1}$]
LT = assumed lifetime of hydroelectric power plants [100 yr]

To calculate 100-year gross emissions, emissions from years 10–100 were added to the brackets at the numerator in Equation (1). To obtain these emissions, the average daily emission as shown on third row in Table 2 (>10 years after flooding) was simply multiplied by 90. Table 2 shows that emissions after 10 years are of the same order of magnitude than emissions from natural lakes and rivers, supporting the hypothesis that a 100-year gross emissions approach probably leads to an overestimation of emissions.

2.2.2. Gross emissions (10 years) based on reservoir-specific measurements

Biogenic GHG emissions vary considerably depending on reservoir characteristics, such as depth or type of soil flooded [12,25]. Therefore, a set of historic reservoir-specific measurements from Hydro-Québec for CO_2 and CH_4 diffusive emissions were used to calculate emissions per kWh for each reservoir using Equation (2). Run-of-the river power plants may also alter the biogenic carbon balance as they may cause some flooding [8]. Therefore, Equation (2) was used for both reservoir and run-of-the-river with flooded land dams. Table A1 in appendix provides raw data and results for 21 water bodies (associated with 25 power plants) for which diffusive emission data were available (no data were available for the remaining 7 power plants). Emissions per kWh were calculated for the average reservoir area, as well as maximum and minimum areas (in parenthesis) as a sensitivity analysis, in order to get results that cover the full operation range.

$$E_{gross\ 10\ specific} = \frac{E_{diff}\ \times\ S}{Prod} \times \frac{10\ yr}{LT} \times 10^{-3} \tag{2}$$

where $E_{gross\ 10\ specific}$ = average emissions per kWh [gCO_2 or $CH_4 \cdot kWh^{-1}$]

E_{diff} = annual diffusive emissions [$mgCO_2$ or $CH_4 \cdot m^{-2} \cdot yr^{-1}$]
S = reservoir surface [km^2]
$Prod$ = average annual electricity production [$GWh \cdot yr^{-1}$]
LT = assumed lifetime of reservoirs [100 yr]

Table 2
Average CO_2 diffusive emissions from 24 hydroelectric reservoirs and natural water bodies as measured and estimated by Hydro-Québec until 2012 for days without ice cover.

	Average CO_2 diffusive emissions ($mgCO_2 \cdot m^{-2} \cdot d^{-1}$)	Number of measurements
≤ 10 years after flooding	3193	4202
>10 years after flooding	1346	3283
Natural lakes	926	3456
Natural rivers	1579	517

The weighted average over the 21 water bodies for which data were available (Table A1) was then calculated. Reservoirs and other impoundments that have no direct associated power plants were let out of the calculation, because no reservoir-specific emission data were available. Finally, to get reservoir emissions per kWh of hydroelectricity produced by all hydropower plants (second column in Table 5), the weighted average was multiplied by annual electricity production from reservoir and run-of-the-river with flooded land hydropower plants (1.42×10^{11} $kWh \cdot yr^{-1}$), and then divided by annual electricity production from all hydropower plants (1.78×10^{11} $kWh \cdot yr^{-1}$).

2.2.3. Net emissions (100 years) from Eastmain-1 reservoir extrapolated to all reservoirs

Teodoru and colleagues performed one of the most comprehensive large-scale assessment of CO_2 and CH_4 emissions associated with the creation of a reservoir (Eastmain-1), including pre- and post-impoundment phases [7]. Therefore, net emissions over a period of 100 years were estimated from this study, and extrapolated to all reservoirs to calculate average emissions per kWh.

Teodoru and colleagues estimated pre-impoundment carbon fluxes (diffusive CO_2 and CH_4 emissions and carbon storage from sedimentation) for three major components of the landscape, i.e. terrestrial (forests and soils), wetlands (fens, bogs, swamps/marshes), and aquatic systems (streams, rivers, lakes). They calculated post-impoundment fluxes for the first four years following impoundment (2006–2009 inclusive) based on measurements, and then proposed an empirical relationship to estimate longer-term carbon fluxes (for 2010 and beyond). Diffusive CO_2 and CH_4, bubbling CH_4, carbon storage from sedimentation, and degassing CO_2 and CH_4 fluxes were included. The empirical relationship provides net emissions. Therefore, pre-impoundment emissions should not be removed from the values obtained for 2010 and beyond. Table 3 presents CO_2 and CH_4 fluxes used for the calculation.

Net emissions per surface area were calculated for CO_2 and CH_4 over a period of 100 years using Equation (3).

$$E_{net\ 100} = \frac{\left\{\sum_{i=2006}^{2009}\left(E_i - E_{preflood}\right) + \sum_{i=2010}^{2105} E_i\right\}}{LT} \times P \times \frac{m_{CO_2 or\ CH_4}}{m_C} \times 10^{-3} \tag{3}$$

where $E_{net\ 100}$ = net emissions (100-year) per surface area [gCO_2 or $CH_4 \cdot m^{-2} \cdot yr^{-1}$]

E_i = emissions of CO_2 or CH_4 for year i as per Table 3 [$mgC \cdot m^{-2} \cdot d^{-1}$]

Table 3
Data used for the calculation of net emissions (100-year) from Eastmain-1 reservoir extrapolated to all reservoirs (data from Ref. [7]).

	Total CO_2 flux ($mgC \cdot m^{-2} \cdot d^{-1}$)	Total CH_4 flux ($mgC \cdot m^{-2} \cdot d^{-1}$)
Pre-impoundment	7	7.6
2006	2279	7.8
2007	1398	8.0
2008	1032	8.8
2009	843	11.9
2010 and beyond[a]	$433.8 + 3,195.9e^{\left(\frac{age}{-1.76}\right)}$	$6.97 - \frac{6.72}{1 + e^{\left(\frac{age - 3.8}{0.46}\right)}}$

[a] Empirical formula proposed by Teodoru and colleagues [7] to estimate emissions from years 6–100 following the creation of the Eastmain-1 reservoir as measures were available for the first 5 years only.

$E_{preflood}$ = pre-impoundment emissions of CO_2 or CH_4 as per Table 3 $[mgC \cdot m^{-2} \cdot d^{-1}]$
P = number of days without ice cover [215d]
m_{CO_2} = molecular weight of CO_2 $[44\ g \cdot mol^{-1}]$
m_{CH_4} = molecular weight of CH_4 $[16\ g \cdot mol^{-1}]$
m_C = molecular weight of C $[12\ g \cdot mol^{-1}]$
LT = assumed lifetime of reservoirs [100 yr]

Finally, net emissions per surface area were multiplied by the sum of average areas for all water bodies included in Tables A1 and A3 ($1.93 \times 10^{10}\ m^2$), and divided by the sum of average annual electricity production.

2.2.4. Net emissions (100 years) from a generic approach

Net emissions were calculated over a period of 100 years using the generic approach proposed in the Product Category Rules (PCR) on electricity, steam, and hot/cold water generation published by the International EPD System [38] as per Equations (4) and (5).

$$E_{CH_4} = S_{CH_4} \times C_{degr} \times D_{degr} \times A_{inund} \times m_{CH_4}/m_C \tag{4}$$

$$E_{CO_2} = (100\% - S_{CH_4}) \times C_{degr} \times D_{degr} \times A_{inund} \times m_{CO_2}/m_C \tag{5}$$

where E_{CH_4} = CH_4 emissions over 100 years $[gCH_4]$

E_{CO_2} = CO_2 emissions over 100 years $[gCO_2]$
S_{CH_4} = share of the carbon degraded in inundated land that is assumed to form CH_4 depending on carbon content and water depth [%]
C_{degr} = carbon content of inundated land $[gC/m^2]$
D_{degr} = degree of carbon degradation assumed during 100 years depending on latitude [%]
A_{inund} = area of land inundated at the retention water level $[m^2]$
m_{CH_4} = molecular weight of CH_4 $[16\ g \cdot mol^{-1}]$
m_C = molecular weight of C $[12\ g \cdot mol^{-1}]$
m_{CO_2} = molecular weight of CO_2 $[44\ g \cdot mol^{-1}]$

The PCR provides generic values for S_{CH_4}, C_{degr} and D_{degr} depending on ecosystem type, latitude (<or >30°) and average reservoir depth (<or >5 m). Emissions for three sets of assumptions were calculated to account for uncertainty: best case, average case, and worst case. All reservoirs are located in three different ecosystem types according to the map provided (i.e. main taiga, southern taiga, and open boreal woodland). C_{degr} depends on ecosystem types. Therefore, the ecosystem type with the lowest C_{degr} value was used for the best case (i.e. open boreal woodland), the one with the highest value for the worst case (i.e. main taiga), and the one with the middle value for the average case (i.e. southern taiga). Moreover, S_{CH_4} can be 0 or 1% for latitudes over 30° depending on the average reservoir depth (<or >5 m). For the best case, 0% was used, while 1% and 0.5% were used for the worst and average cases respectively. The sum of average areas for all water bodies included in Tables A1 and A3 ($1.93 \times 10^{10}\ m^2$) was used for A_{inund}. Total emissions, as provided by Equations (4) and (5), were then divided by 100 years, and by the sum of average annual electricity production.

2.2.5. Generic values from the literature

A few recent publications propose average values for CO_2 and CH_4 emissions from hydropower reservoirs based on existing literature. Hertwich [29] supplemented emission data from Barros and colleagues [6] with information on electricity generation from various sources to get average emissions of 85 $gCO_2 \cdot kWh^{-1}$ and 3 $gCH_4 \cdot kWh^{-1}$ for electricity produced by reservoir power plants. To get reservoir emissions per kWh total hydroelectricity produced, these values were multiplied by the average annual production for all the reservoir and run-of-the-river with flooded land power plants as per Table A1 ($1.42 \times 10^{11}\ kWh \cdot yr^{-1}$), and then divided by the total average annual hydroelectricity production from all hydropower plants owned by Hydro-Québec ($1.78 \times 10^{11}\ kWh \cdot yr^{-1}$).

Scherer & Pfister [30] also proposed average reservoir emissions from a statistical analysis performed among 1500 hydropower plants, leading to average emissions of 173 $gCO_2 \cdot kWh^{-1}$ and 2.95 $gCH_4 \cdot kWh^{-1}$ for electricity produced by reservoir power plants. To get reservoir emissions per kWh total hydroelectricity produced, these values were multiplied by the average annual production for all the reservoir and run-of-the-river with flooded land power plants as per Table A1 ($1.42 \times 10^{11}\ kWh \cdot yr^{-1}$), and then divided by the total average annual hydroelectricity production from all hydropower plants owned by Hydro-Québec ($1.78 \times 10^{11}\ kWh \cdot yr^{-1}$).

Finally, Deemer and colleagues [25] produced a global estimate of reservoir emissions from existing literature. For hydroelectric reservoirs, emissions vary from 386 to 660 $mgC \cdot m^{-2} \cdot d^{-1}$ for CO_2 and from 24 to 112 $mgC \cdot m^{-2} \cdot d^{-1}$ for CH_4. These values were multiplied by the ratio of molecular weights, and by the sum of average areas for all water bodies included in Tables A1 and A3 ($1.93 \times 10^{10}\ m^2$), and then divided by the sum of average annual electricity production.

2.2.6. Net emissions (100 years) from the G-res model

Net emissions over a period of 100 years were also calculated using the G-res model, a publicly available web-based tool developed by an international team of researchers supported by the International Hydropower Association (IHA) and the UNESCO Chair in Global Environmental Change [31]. The G-res tool is based on several statistical relationships, derived from the global analysis of published measured GHG fluxes (diffusive, ebullitive and degassing) as functions of site-specific climate variables, reservoir age and shape, and flooded soil carbon content (see Ref. [31] for details). It also accounts for pre-impoundment GHG emissions, simulates the long-term evolution of GHG emissions after impoundment, and following the approach outlined in Ref. [8], accounts for the CO_2 emissions that would have occurred even in the absence of the reservoir. The G-res tool also provides an estimate of the reservoir emissions that are fueled by human activities occurring in the catchment. However, since hydropower reservoirs in Quebec are in isolated locations where no other significant human activities occur, this last element is not relevant for our case and will not be accounted for.

Post-impoundment emissions from this approach account for bubbling CH_4 fluxes, diffusive CO_2 and CH_4 fluxes at the reservoir surface, and degassing CH_4 fluxes. They are estimated based on measured GHG fluxes data from the literature for different reservoir characteristics, such as age, size, carbon contained in the flooded land, and adapted for temperature. Since there is a limited number of available publications regarding CH_4 bubbling and degassing emissions, as well as how they vary over time, the values calculated by the G-res model are probably conservative for boreal regions.

Pre-impoundment fluxes are estimated for nine potential types of land cover, i.e. wetland, forest, cropland, water bodies, grassland, bare areas, permanent snow and ice, and settlements, and for different climate zones (boreal, temperate, subtropical and tropical) and soil types (organic or mineral), using emission factors such as those published by the IPCC [37]. Total CO_2 and CH_4 emissions (gCO_2 or

$CH_4 \cdot yr^{-1}$) were calculated summing total net emissions of all water bodies (Table A4, 2.5% and 97.5% confidence intervals are included in parenthesis to account for uncertainty).

2.3. Carbon footprint of electricity distributed in the province of Québec

In 2014, the International Reference Centre for the Life Cycle of Products, Processes and Services (CIRAIG) conducted for Hydro-Québec an LCA of the electricity generated, purchased, transmitted, and distributed in the province of Québec [39]. The functional unit for this study was "the generation or purchase, transmission and distribution of 1 kWh of electricity in Québec through Hydro-Québec's main power system in 2012".

Electricity is generated by Hydro-Québec's power plants, or purchased from independent producers in the province or from power systems in adjacent provinces or U.S. states. Power from all these facilities is then brought to the load centers by the transmission system, operated by the division Hydro-Québec TransÉnergie. The transmission system includes lines and substations. Lines comprise support structures (towers), equipment and conductors. Substations perform switching operations, and maintain or transform the voltage. In 2012, the transmission system had 33,911 km of lines and 516 transformer substations. The distribution system, operated by the division Hydro-Québec Distribution, includes all the facilities needed to distribute power from the transformer substations to the customer connection points. Most of the distribution system is overhead (more than 2,700,000 poles and 114,649 km of lines), but some is underground (3900 km).

Data collection was performed through sampling; a representative sample of the various activities of each division was first defined. Primary data, obtained directly from Hydro-Québec and its suppliers, were collected for this sample, and extrapolated to cover the rest of the power system. Overall, all life cycle phases were included. For end-of-life, dismantling and waste management were included for transmission and distribution equipment, but not for dams. Secondary data and assumptions were gathered to complement the information supplied by Hydro-Québec divisions, consisting of the ecoinvent database [40], the CIRAIG in-house database, available public databases, a literature review, and the contribution of a number of experts. Inventory data from this LCA have since been integrated to the ecoinvent version 3 database [40] to model electricity produced, transmitted and distributed in the province of Québec.

Since the first version of the study, published in 2014 [39], updates have occurred and been integrated to ecoinvent to take into account the changing composition of the generation mix (the amount of electricity produced and purchased by the different sources), the new infrastructures built (new generation plants, transmission lines, transformation posts and distribution lines), and new operation data based on the state-of-the-art research (e.g. GHG emissions from reservoirs).

For this study, the process 'market for electricity, low voltage, CA-QC' from the latest version of the ecoinvent database (version 3.5) was used and adapted. The grid composition was changed for that of 2017 in the associated 'market for electricity, high voltage, CA-QC' process, reservoir emissions were changed for those of the method selected in section 2.2, and the carbon footprint of 1 kWh of electricity distributed on the grid was calculated. Table 4 presents the grid composition for 2017 as per Hydro-Québec data with which we adapted the 'market for electricity, high voltage, CA-QC' process.

Three processes from Table 4 include reservoir emissions: 1) 'electricity production, hydro, reservoir, non-alpine region, CA-QC', 2) 'electricity, high voltage, hydro, import from CA-ON, CA-QC', and 3) 'electricity, high voltage, import from CA-NF, CA-QC'. The values of reservoir CO_2 and CH_4 emissions were changed for these three processes using the G-res model approach, following our analysis as presented in section 3. For the 'electricity, high voltage, import from CA-NF, CA-QC' process, net emissions in $gCO_2 \cdot yr^{-1}$ and $gCH_4 \cdot yr^{-1}$ for the Churchill reservoir in Table A4 were used. Indeed, 100% of the electricity imported from Newfoundland is produced by the Churchill Falls power plant. These values were then divided by the total amount of electricity produced by Churchill Falls in 2017, i.e. 30,927 GWh [41], to get emissions per kWh. For the 'electricity production, hydro, reservoir, non-alpine region, CA-QC' process, total net emissions, without Churchill reservoir, were used as per Table A4, and divided by the total amount of electricity produced by reservoir power plants in 2017 according to Hydro-Québec, i.e. 105,264 GWh. Hydropower produced and imported from Ontario is represented by the 'electricity, high voltage, hydro, import from CA-ON, CA-QC' process. As data for Ontario reservoirs are not available, and as hydropower from Ontario represents only 0.014% of the grid, values for Québec were used as a proxy for reservoir emissions.

Table 4

Grid composition for 2017 as integrated in the 'market for electricity, high voltage, CA-QC' ecoinvent process (data from Hydro-Québec).

Production Process	%
electricity production, hydro, reservoir, non-alpine region, CA-QC	47.5255
electricity production, hydro, run-of-river, CA-QC	34.6761
electricity, high voltage, import from CA-NF, CA-QC	11.8371
electricity, high voltage, hydro, import from CA-ON, CA-QC	0.0140
electricity production, wind, >3 MW turbine, onshore, CA-QC	3.0665
electricity production, wind, 1–3 MW turbine, onshore, CA-QC	1.3939
electricity production, wind, <1 MW turbine, onshore, CA-QC	0.1858
electricity production, oil, CA-QC	0.00073
heat and power co-generation, biogas, gas engine, CA-QC	0.0813
heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014, CA-QC	0.8849
electricity, high voltage, import from CA-NB, CA-QC	0.0104
electricity, high voltage, import from CA-ON	0.2677
electricity, high voltage, import from NPCC, US only, CA-QC	0.0560

Finally, the carbon footprint of 1 kWh electricity as distributed in the province of Québec was calculated from the 'market for electricity, low voltage, CA-QC' process using the ecoinvent v.3.1 IPCC2013 GWP100 method in the OpenLCA 1.7.0 software (https://openlca.org).

3. Results and discussion

Table 5 presents reservoir emissions per kWh of electricity from reservoir and run-of-the-river with flooded land hydropower plants (first column), and per kWh of electricity from all hydropower plants (second column), for the different approaches presented in section 2.2. Results in gCO_2eq/kWh have been calculated using GWP100 and GTP100, as recommended by the UNEP/SETAC Life Cycle Initiative following a consensus-building workshop [42]. Both indicators are published by the IPCC [43]. While GWP100 represents the ratio of cumulative radiative forcing over 100 years caused by a unit-mass pulse emission of a given GHG relative to that of CO_2, GTP100 represents the absolute change in global mean surface temperature 100 years following a unit-mass pulse emission of a given GHG relative to that of CO_2. Fig. 1 presents in a bar chart the results for GHG emissions per unit electricity produced by reservoir and run-of-the-river with flooded land power plants using GWP100 (fifth column of Table 5).

First four results (average gross emission over 10 and 100 years,

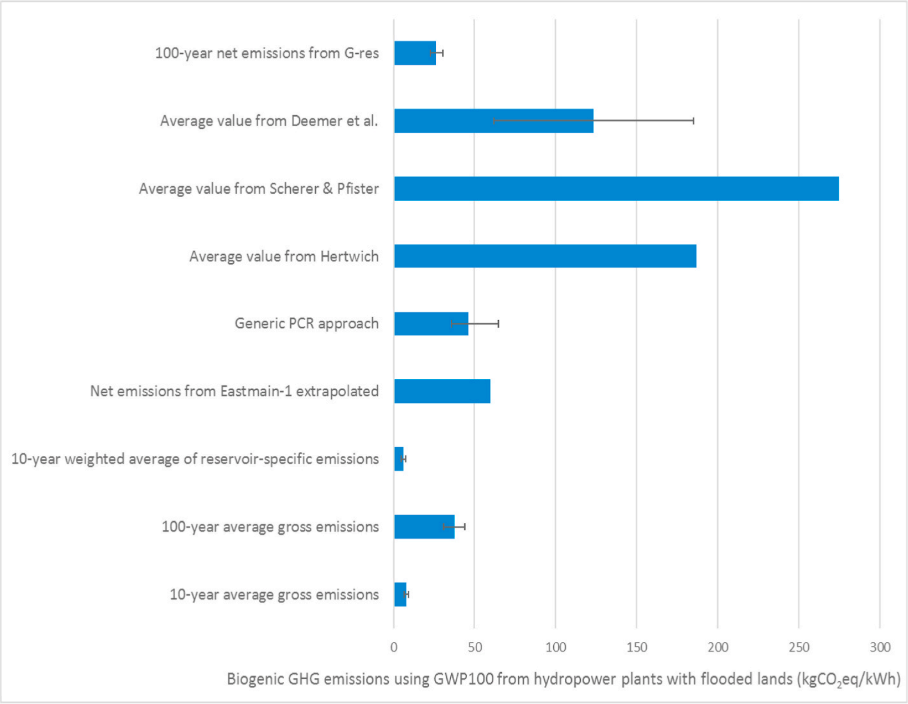

Fig. 1. Reservoir emissions estimated using different approaches per unit electricity produced by reservoir and run-of-the river with flooded land power plants using GWP100.

weighted average of reservoir-specific gross emissions over 10 years, and net emission from Eastmain-1 reservoir over 100 years extrapolated to all reservoirs) are based on measurements taken on Hydro-Québec reservoirs. These results are therefore more representative of the given context than those obtained from a generic approach (such as in section 2.2.4) or a world average value (such as in section 2.2.5). The best approach is to calculate the net emission over 100 years as done for the Eastmain-1 reservoir, following an intensive measurement campaign of pre- and post-impoundment fluxes. Indeed, this approach includes all types of fluxes (diffusion, bubbling, degassing, carbon storage), and distinguishes between natural and anthropogenic fluxes, as it calculates a net emission over 100 years. However, such comprehensive studies are rare as they are very expensive and require considerable sampling efforts. For the province of Québec, the Eastmain-1 reservoir is the only one for which results are currently available. Results for a second set of reservoirs (Romaine complex) will be available in the coming years. Extrapolating the results of one study to other reservoirs is problematic, as they are all very different, and emissions highly depend on the reservoir characteristics. Eastmain-1 is a relatively shallow reservoir, impounding high carbon content soil, which usually leads to higher emissions. Emissions are therefore overestimated when these results are extrapolated to all reservoirs, as done in section 2.2.3. As shown in Table 5, emissions of CO_2 and CH_4 are higher for this approach (respectively 51.0 and 0.26 g/kWh) than for the weighted average of reservoir-specific gross emission over 10 years (respectively 5.4 and 0.02 g/kWh) and the average gross emission over 10 years (7.8 gCO_2/kWh) and over 100 years (37.4 gCO_2/kWh).

As reservoir emissions depend on reservoir characteristics, the reservoir-specific approach (section 2.2.2) is probably better than the average approach (section 2.2.1). However, data were not available for all reservoirs, which could bias the results. In particular, reservoirs and flooded lands that are not associated directly to a power plant (Table A3) were left out because of missing data. This could explain the lower value obtained with this approach compared with that obtained with the average gross emission over 10 years approach (5.4 gCO_2/kWh versus 7.8 gCO_2/kWh). Moreover, reservoir-specific measures have been taken at different ages, which might lead to an under- or over-estimation of the results. Therefore, the reservoir-specific approach has the advantage of considering the characteristics of reservoirs, but not the age. Both these approaches (sections 2.2.1 and 2.2.2) are based on gross emissions, because no data about pre-impoundment emissions are available, and include only CO_2 diffusive emissions.

The generic approach proposed by a PCR (section 2.2.4) is very simple to use. However, uncertainties are very high as it is not based on any measurements or modelling. The calculation includes parameters in order to consider some reservoir characteristics, such as the latitude and water depth, but this approach is not recommended if data based on measurements or modelling are available. Average values from the literature (section 2.2.5) all show very high results compared with other approaches (85 gCO_2/kWh and 3.0 gCH_4/kWh for [29], 173 gCO_2/kWh and 3.0 gCH_4/kWh for [30], 34.6–59.2 gCO_2/kWh and 0.8–3.7 gCH_4/kWh for [25]). These results are based on data published in the literature from different regions of the world. They include reservoirs in tropical zones, for which emissions can be very high compared with

Table 5
Reservoir emissions estimated using different approaches per unit electricity produced by reservoir and run-of-the-river with flooded land power plants (first column) and per unit electricity produced by all hydropower plants owned by Hydro-Québec (second column).

Approach	CO_2 (gCO_2/kWh)		CH_4 (gCH_4/kWh)		GHGs using GWP100 (gCO_2eq/kWh)		GHGs using GTP100 (gCO_2eq/kWh)	
	With flooded land only	All hydropower plants	With flooded land only	All hydropower plants	With flooded land only	All hydropower plants	With flooded land only	All hydropower plants
2.2.1 Average gross emissions (10 years)[a]	7.8 (6.5–9.2)	6.2 (5.2–7.3)	NA	NA	7.8 (6.5–9.2)	6.2 (5.2–7.3)	7.8 (6.5–9.2)	6.2 (5.2–7.3)
2.2.1 Average gross emissions (100 years)[a]	37.4 (31.0–43.9)	29.9 (24.8–35.0)	NA	NA	37.4 (31.0–43.9)	29.9 (24.8–35.0)	37.4 (31.0–43.9)	29.9 (24.8–35.0)
2.2.2 Weighted average of reservoir-specific gross emissions (10 years)[a]	5.4 (4.2–6.4)	4.2 (3.4–5.1)	0.02 (0.02–0.03)	0.02 (0.01–0.02)	6.1 (4.9–7.4)	4.9 (3.7–5.8)	5.6 (4.4–6.7)	4.4 (3.5–5.3)
2.2.3 Net emissions (100 years) from Eastmain-1 extrapolated to all reservoirs	51.0	40.7	0.26	0.21	59.8	47.8	53.9	43.0
2.2.4 Net emissions (100 years) from a generic approach (PCR)	43.6 (35.9–57.7)	34.8 (28.6–46.1)	0.08 (0.00–0.21)	0.06 (0.00–0.17)	46.3 (35.9–64.8)	36.8 (28.6–51.9)	44.5 (35.9–60.0)	35.5 (28.6–48.0)
2.2.5 Average value from Hertwich [29]	85	67.8	3.0	2.4	187	149	118	94
2.2.5 Average value from Scherer & Pfister [30]	173	138	3.0	2.4	275	219	206	164
2.2.5 Min and max values from Deemer et al. [25]	34.6–59.2	27.6–47.2	0.8–3.7	0.6–2.9	61.8–185.0	48.0–145.8	43.4–99.9	34.2–79.1
2.2.6 Net emissions (100 years) from G-res[b]	16.5 (14.7–18.6)	13.2 (11.7–14.8)	0.29 (0.23–0.35)	0.23 (0.19–0.28)	26.4 (22.5–24.3)	21.0 (18.1–24.3)	19.7 (17.2–22.5)	15.7 (13.8–17.9)

[a] Emissions for average area, emissions for minimum and maximum area in parenthesis.
[b] Result from G-res, 2.5% and 97.5% confidence interval in parenthesis.

Table 6
Summary of the comparative analysis of different approaches to estimate reservoir emissions.

Approach	2.2.1 Gross emissions based on a set of historic measurements	2.2.2 Gross emissions based on reservoir-specific measurements	2.2.3 Net emissions from Eastmain-1 reservoir extrapolated to all reservoirs	2.2.4 Net emissions from a generic PCR approach	2.2.5 Generic values from the literature	2.2.6 Net emissions from G-res
Type of emissions	Diffusion (CO_2)	Diffusion (CO_2 and CH_4)	Diffusion (CO_2 and CH_4), bubbling (CH_4), degassing (CO_2 and CH_4)	Generic overall estimation	Variable (from different studies)	Diffusion (CO_2 and CH_4), bubbling (CH_4), degassing (CH_4)
Gross or net emissions	Gross	Gross	Net	Net	Gross	Net
Reservoir-specific	No	Yes	Yes for Eastmain-1, no for others	No	No	Yes
Geography-specific	Yes	Yes	Yes	Yes	No	Yes
Number of impoundments	24 unspecified impoundments	21 specific impoundments	One impoundment, extrapolated to others	One generic value	Several impoundments all around the world	Specific data for all impoundments
Data from direct measurements, modelling or generic approach	Direct measurements	Direct measurements	Direct measurements (first four years) and modelling	Generic approach	Direct measurements, modelling	Modelling

those in boreal zones, especially for methane. As they are not specific to the context of the province of Québec, they are less representative. A good way to improve this type of approach would be to divide the data collected into categories that would better reflect, at least, the climate zone of the reservoir. However, even this approach can generate inappropriate results, since some reservoirs in tropical regions are less emitting because of the climate, soil and design characteristics.

Finally, the results from the last approach (section 2.2.6) are the net emissions over 100 years as calculated using the G-res model. The advantages of this approach are that it takes into account the specific characteristics of the reservoirs (e.g. size, carbon contained in the flooded land, temperature) in the estimation, and that all types of fluxes (diffusion, bubbling, degassing) are included. Moreover, it is based on a net 100-year emission approach, as pre- and post-impoundment fluxes are estimated, and it allows including all reservoirs and water bodies. The model could be used for any geographical location, as it can be calibrated using local parameters. Moreover, uncertainty can be quantified and expressed using 2.5% and 97.5% confidence intervals. The results from this approach (16.5 gCO_2/kWh and 0.29 gCH_4/kWh) are in between that of average gross emission over 10 years (7.8 gCO_2/kWh) and weighted average of reservoir-specific gross emissions over 10 years (5.4 gCO_2/kWh and 0.02 gCH_4/kWh) and that of net emissions over 100 years from Eastmain-1 extrapolated to all reservoirs (51.0 gCO_2/kWh and 0.26 gCH_4/kWh). It might be difficult to select the best approach since they all have different limitations (e.g. type of flux considered, based on measurement versus modelling, reservoir-specific versus generic). Table 6 presents a summary of the comparative analysis performed on all the approaches. In the absence of site-specific data to calculate the net GHG emission based on the five types of fluxes as per Eastmain-1, the use of G-res is considered the most reliable and comprehensive approach. G-res has therefore been used to model all the reservoirs and flooded lands according to their specific characteristics, and to calculate their net emissions over 100 years to be included in the carbon footprint of electricity distributed in the province of Québec.

The results from G-res, as per Table A4, were used to calculate net biogenic GHG emissions per kWh produced for each hydropower complex. To do so, all power plants (Tables A1 and A2) and water bodies that are not directly associated to a given power plant (Table A3), that are in the same watershed, were grouped together. Total annual GHG emissions from all water bodies were then divided by total annual electricity production from all power plants situated in the watershed. Results, as per Table A5, show that emissions vary from one hydropower complex to another, from 0 (for watersheds without any reservoirs or flooded lands) to 73.2 $gCO_2eq \cdot kWh^{-1}$.

As per section 2.3, the carbon footprint of electricity distributed in Québec, using the 2017 grid composition and reservoir emissions from the G-res model approach, is 34.5 $gCO_2eq \cdot kWh^{-1}$. It represents an increase of 42% compared with the carbon footprint calculated from the process currently available in ecoinvent, which is 24.3 $gCO_2eq \cdot kWh^{-1}$. This increase is caused by biogenic carbon emissions from flooded lands that are higher using G-res than the values found in ecoinvent, which were calculated in 2014 using a 10-year gross emission approach based on a set of measurements (such as in section 2.2.1).

Biogenic emissions from flooded lands contribute to about 70% of the carbon footprint of the electricity distributed in the province of Québec in 2017. Emissions associated with the construction of hydropower infrastructures in Québec and Newfoundland (Churchill complex) contribute to about 12% of the carbon footprint of the electricity distributed in the province. Emissions from electricity production from non-hydro sources in Québec (wind, biomass, oil) represent about 5% of the carbon footprint, while those associated with the generation of imported electricity from other jurisdictions than Newfoundland represent about 1.4%. Finally, transmission, distribution, and operations (including losses) contribute to about 10% of the carbon footprint. Regarding hydroelectricity production only, i.e. without transmission and distribution, the contribution of the construction of infrastructures to GHG emissions is much higher for run-of-the-river power plants (96%) than for reservoir power plants (7.5%) as they do not cause any biogenic GHG emissions.

4. Conclusions

This paper presents a comparative analysis of different approaches to quantify biogenic CO_2 and CH_4 emissions from hydropower reservoirs in the province of Québec (Canada). These approaches differ according to various aspects, such as the type (diffusion, bubbling, degassing) and nature (CO_2 and CH_4) of emissions considered, the use of reservoir- and/or geography-specific data, the number of impoundments covered, and the technique used to estimate emissions (measurements, modelling, generic). In the absence of a comprehensive set of data for all reservoirs, that include pre- and post-impoundments diffusive, bubbling and degassing CO_2 and CH_4 emissions, the G-res model, supported by the IHA and the UNESCO Chair in Global Environmental Change as the result of an international multi-stakeholder research project [31], has been used. Since it can be calibrated for any geographical location using local parameters, this approach takes into account all types of emissions, as well as the specific characteristics of each reservoir, which highly influence the results, as shown in this paper.

Using the G-res model, biogenic emissions were estimated for all the hydropower reservoirs in Québec, as well as for the Churchill reservoir for hydropower imported from Newfoundland-Labrador, a neighbouring province. These results were then used to calculate an updated value for the carbon footprint of electricity distributed in the province of Québec in 2017. The result obtained is 34.5 $gCO_2eq \cdot kWh^{-1}$, which is 42% higher than the value currently available in the ecoinvent database. The carbon footprint has increased because G-res considers all flooded lands and all types of flux, which was not the case for the approach used before.

In this paper, biogenic emissions from reservoirs were calculated as average emissions over 100 years, meaning that the temporal profile has been ignored. However, the largest share of these emissions occur during the first 10–15 years following creation of the reservoir [8,12]. This is very different from a thermal power plant, which releases more or less constant GHG emissions over its lifetime. Some hydropower plants in Québec are several decades old, meaning that their reservoirs currently release very little biogenic carbon emissions. By contrast, recent hydropower complexes, such as Eastmain or Romaine, probably still releases high amounts of biogenic carbon, more than their average emission calculated over 100 years. To better represent the current and future carbon footprint of electricity produced in the province, a dynamic LCA approach [44] could be used to consider the temporal profile of GHG emissions for each power plant according to the year of its construction. This would provide a better assessment of the potential contribution of electricity production to current and future global warming.

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Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1
Reservoir and run-of-the-river with flooded lands hydropower plants (data from Hydro-Québec)

Power plant	Water body	Type	Construction year	Maximum area	Minimum area	Average area[a]	Electricity production 2011–2015
				km^2	km^2	km^2	$GWh \cdot yr^{-1}$
Bersimis-1	Pipmuacan	Reservoir	1956	859	608	733.5	6156
Bersimis-2	Betsiamites	Run-of-the-river	1959	41.4	NA[h]	41.4[d]	3397
Brisay	Caniapiscau	Reservoir	1993	4282	1659	2970.5	1988
Eastmain-1 and 1-A	Eastmain-1	Reservoir	2006	624	327	475.5	5744[c]
Hart-Jaune	Petit lac Manicouagan	Reservoir	1960	227.9	NA[h]	227.9[d]	244.8
Laforge-1	Laforge-1	Reservoir	1993	1166	276	721	4104
Laforge-2	Laforge-2	Run-of-the-river	1984	260	NA[h]	260[d]	1657
La Grande-1	La Grande	Run-of-the-river	1993	68	65	66.5	8381
La Grande-2-A and Robert-Bourassa	Robert-Bourassa	Reservoir	1979	2813	2271	2542	43142[c]
La Grande-3	La Grande-3	Reservoir	1984	2536	1599	2067.5	12913
La Grande-4	La Grande-4	Reservoir	1983	707	NA[h]	707[d]	14122
Manic-1 and McCormick[i]	Manicouagan	Run-of-the-river	1951	11.8	11.8	11.8	2632[c]
Manic-2 (Jean-Lesage)	Manic-2	Run-of-the-river	1965	114	110	112	5402
Manic-3 (René-Lévesque)	Manic-3	Run-of-the-river	1971	217	213	215	5266
Manic-5 and 5-PA	Manicouagan	Reservoir	1964	1926	1628	1777	6621[c]
Mercier	Baskatong	Reservoir	1927	398	77	237.5	267
Mitis-1 and Mitis-2	Mitis	Run-of-river	1924	NA[h]	NA[h]	18.5	57.6
Outardes-3	Outardes-3	Run-of-the-river	1969	11	NA[h]	11[d]	4279
Outardes-4	Outardes-4	Reservoir	1970	677	487	582	3395
Rapide-7	Decelles	Reservoir	1941	237	138	187.5	310.6
Rapide-Blanc	Blanc	Reservoir	1934	83	34	58.5	957
Romaine-1	Romaine-1	Run-of-the-river	2015	12.6	NA[h]	12.6[d]	1225.4[e]
Romaine-2	Romaine-2	Reservoir	2014	85.8	NA[h]	85.8[d]	2798.2[f]
Romaine-3	Romaine-3	Reservoir	2017	38.6	NA[h]	38.6[d]	1260.2[g]
Sainte-Marguerite-3	Sainte-Marguerite-3	Reservoir	1998	253	214	233.5	2608
Sarcelle	Opinaca	Run-of-the-river	2012	1040	NA[h]	1040[d]	631
Toulnustouc	Lac Sainte-Anne	Reservoir	1957	259	174	216.5	2534
TOTAL				**18,966.6**	**12,334.6**	**15,650.6**	**142,092.8**

Power plant	Water body	Type	CO_2 annual flux[b]	CH_4 annual flux[b]	Gross 10-year CO_2 emissions average	Gross 10-year CH_4 emissions average	Gross 10-year CO_2 emissions max	Gross 10-year CH_4 emissions max	Gross 10-year CO_2 emissions min	Gross 10-year CH_4 emissions min
			$mgCO_2 \cdot m^{-2} \cdot yr^{-1}$	$mgCH_4 \cdot m^{-2} \cdot yr^{-1}$	$gCO_2 \cdot kWh^{-1}$	$gCH_4 \cdot kWh^{-1}$	$gCO_2 \cdot kWh^{-1}$	$gCH_4 \cdot kWh^{-1}$	$gCO_2 \cdot kWh^{-1}$	$gCH_4 \cdot kWh^{-1}$
Bersimis-1	Pipmuacan	Reservoir	No data available							
Bersimis-2	Betsiamites	Run-of-the-river	238588	419	0.3	0.00	0.3	0.00	0.3	0.00
Brisay	Caniapiscau	Reservoir	435849	706	65.1	0.11	93.9	0.15	36.4	0.06
Eastmain-1 and 1-A	Eastmain-1	Reservoir	488696	2267	4.0	0.02	5.3	0.02	2.8	0.01
Hart-Jaune	Petit lac Manicouagan	Reservoir	No data available							
Laforge-1	Laforge-1	Reservoir	458273	2416	8.1	0.04	13.0	0.07	3.1	0.02
Laforge-2	Laforge-2	Run-of-the-river	359174	2041	5.6	0.03	5.6	0.03	5.6	0.00
La Grande-1	La Grande	Run-of-the-river	496684	1579	0.4	0.00	0.4	0.00	0.4	0.00

(continued on next page)

Table A.1 (*continued*)

Power plant	Water body	Type	CO_2 annual flux[b]	CH_4 annual flux[b]	Gross 10-year CO_2 emissions average	Gross 10-year CH_4 emissions average	Gross 10-year CO_2 emissions max	Gross 10-year CH_4 emissions max	Gross 10-year CO_2 emissions min	Gross 10-year CH_4 emissions min
			$mgCO_2 \cdot m^{-2} \cdot yr^{-1}$	$mgCH_4 \cdot m^{-2} \cdot yr^{-1}$	$gCO_2 \cdot kWh^{-1}$	$gCH_4 \cdot kWh^{-1}$	$gCO_2 \cdot kWh^{-1}$	$gCH_4 \cdot kWh^{-1}$	$gCO_2 \cdot kWh^{-1}$	$gCH_4 \cdot kWh^{-1}$
La Grande-2-A and Robert-Bourassa	Robert-Bourassa	Reservoir	536589	2602	3.2	0.02	3.5	0.02	2.8	0.01
La Grande-3	La Grande-3	Reservoir	497672	2523	8.0	0.04	9.8	0.05	6.2	0.03
La Grande-4	La Grande-4	Reservoir	495967	2529	2.5	0.01	2.5	0.01	2.5	0.01
Manic-1 and McCormick	Manicouagan	Run-of-the-river	777529	2778	0.3	0.00	0.3	0.00	0.3	0.00
Manic-2 (Jean-Lesage)	Manic-2	Run-of-the-river	89704	290	0.2	0.00	0.2	0.00	0.2	0.00
Manic-3 (René-Lévesque)	Manic-3	Run-of-the-river	284911	2522	1.2	0.01	1.2	0.01	1.2	0.01
Manic-5 and 5-PA	Manicouagan	Reservoir	491266	1964	13.2	0.05	14.3	0.06	12.1	0.05
Mercier	Baskatong	Reservoir	335660	720	29.8	0.06	50.0	0.11	9.7	0.02
Mitis-1 and Mitis-2	Mitis	Run-of-river	No data available							
Outardes-3	Outardes-3	Run-of-the-river	19805	33	0.0	0.00	0.0	0.00	0.0	0.00
Outardes-4	Outardes-4	Reservoir	604232	2301	10.4	0.04	12.0	0.05	8.7	0.03
Rapide-7	Decelles	Reservoir	No data available							
Rapide-Blanc	Blanc	Reservoir	446401	1045	2.7	0.01	3.9	0.01	1.6	0.00
Romaine-1	Romaine-1	Run-of-the-river	No data available							
Romaine-2	Romaine-2	Reservoir	777151	809	2.4	0.00	2.4	0.00	2.0	0.00
Romaine-3	Romaine-3	Reservoir	No data available							
Sainte-Marguerite-3	Sainte-Marguerite-3	Reservoir	588874	949	5.3	0.01	5.7	0.01	4.8	0.01
Sarcelle	Opinaca	Run-of-the-river	523476	2399	86.3	0.40	86.3	0.40	86.3	0.40
Toulnustouc	Lac Sainte-Anne	Reservoir	685566	2854	5.9	0.02	7.0	0.03	4.7	0.02
Weighted average					**5.3**	**0.02**	**6.4**	**0.03**	**4.2**	**0.01**

NA = Non available.

[a] Average area = (Maximum area – Minimum area)/2 + Minimum area.

[b] Annual flux = Average daily flux from historical measurements * Number of days without ice cover per year.

[c] When two power plants are located on the same water body, electricity production is the sum of both power plants' production.

[d] If no minimum area is available, the maximum area is used as average area.

[e] Average electricity production for 2016 to 2018 as the power plants started its operation in the course of 2015.

[f] Average electricity production for 2015 to 2018 as the power plants started its operation in the course of 2014.

[g] Average electricity production for 2018 only as the power plants started its operation in the course of 2017.

[h] To calculate the sum of minimum or maximum surfaces, we used the average surface for this reservoir.

[i] The McCormick power plant is owned by Hydro-Québec at 60% (40% is private and bought by Hydro-Québec).

Table A.2
Run-of-the-river without flooded lands hydropower plants (data from Hydro-Québec)

Power plant	Water body	Construction year	Electricity production 2011–2015 ($GWh \cdot yr^{-1}$)
Beauharnois	Saint-Laurent	1932	12180.3
Beaumont	Saint-Maurice	1958	1389.4
Bryson	Outaouais	1925	366.5
Carillon	Outaouais	1962	2535.4
Chelsea	Gatineau	1927	781.4
Chute-Allard	Saint-Maurice	2008	380.1
Chute-Bell	Rouge	1915	1.1
Chute-des-Chats	Outaouais	1931	571.9
Chute-Hemmings	Saint-François	1925	123.4
Drummondville	Saint-François	1919	58.9
Grand-Mère	Saint-Maurice	1916	66.6
Hull-2	Outaouais	1920	127.5
La Gabelle	Saint-Maurice	1924	771.7
La Tuque	Saint-Maurice	1940	1391.8
Les Cèdres	Saint-Laurent	1914	391.2
Outardes-2	Outardes	1978	2529.7
Paugan	Gatineau	1928	834.1
Première-Chute	Outaouais	1968	636.4
Péribonka	Péribonka	2007	2592.6
Rapide-2	Outaouais	1954	324.8
Rapides-des-Coeurs	Saint-Maurice	2008	513.1
Rapides-des-Quinze	Outaouais	1923	607.7
Rapides-des-Îles	Outaouais	1966	768.4
Rapides-Farmer	Gatineau	1927	468.5
Rivière-des-Prairies	des Prairies	1929	264.7
Rocher-de-Grand-Mère	Saint-Maurice	2004	1216.9
Saint-Narcisse	Batiscan	1926	113.6
Sept-Chutes	Sainte-Anne	1916	88.9
Shawinigan-2	Saint-Maurice	1911	1052.4
Shawinigan-3	Saint-Maurice	1948	1071.9
Trenche	Saint-Maurice	1950	1582.6

Table A.3
Reservoirs and connectors that are not directly associated with a power plant

Water body	Comment	Area (km^2)	Construction year
Boyd	Upstream from the Robert-Bourassa reservoir	124.8	1980
Cabonga	Located in La the Vérendrye wildlife preserve	434	1928
Châteauvert	Manouane-C dam located in the St-Maurice river basin	27.97	1952
Cinconsine	Located in the St-Maurice river basin	12.4	1942
Dozois	Located in the La Vérendrye wildlife preserve	311.82	1965
Gouin	Source of the St-Maurice river	1357.44	1918
Kempt	Manouane-A dam located in the St-Maurice river basin	175.26	1941
Manouane	Manouane-B dam located in the St-Maurice river basin	52.6	1953
Mékinac	Located in the St-Maurice river basin	22.69	2011
Mondonac	Located in the St-Maurice river basin	23.13	1944
Rupert downstream	Upstream from the Eastmain-1 reservoir	116.8	2009
Rupert upstream	Upstream from the Eastmain-1 reservoir	254	2009
Sakami	Upstream from the Robert-Bourassa reservoir	605.6	1980
Taureau	Matawin dam	98.46	1930
TOTAL		**3616.97**	

Table A.4
Net 100-year emissions calculated using the G-res model for all reservoir and run-of-the-river with flooded lands hydropower plants as well as reservoirs and connectors that are not directly associated with a power plant (2.5% and 97.5% confidence intervals are in parenthesis)

Power plant/Water body	Reservoir area (km^2)	Net CO_2 emissions ($gCO_2 \cdot m^{-2} \cdot yr^{-1}$)	Net CH_4 emissions ($gCH_4 \cdot m^{-2} \cdot yr^{-1}$)	Net CO_2 emissions ($gCO_2 \cdot yr^{-1}$)	Net CH_4 emissions ($gCH_4 \cdot yr^{-1}$)
Bersimis-1	787.6	130.5 (118.3:142.8)	4.8 (4.0:5.8)	1.03 (0.93:1.12)^{E}+11	3.79 (3.16:4.54)^{E}+9
Bersimis-2	42.1	149.8 (141.7:158.7)	0.7 (0.5:0.8)	6.30 (5.96:6.68)^{E}+9	2.78 (2.27:3.39)^{E}+7
Rupert upstream	227.7	96.0 (84.5:107.6)	1.5 (1.2:1.8)	2.19 (1.92:2.45)^{E}+10	3.31 (2.70:4.03)^{E}+8
Rupert downstream	116.8	−5.6 (−17.4:7.1)	0.7 (0.5:1.1)	−6.59 (−20.4:8.31)^{E}+8	8.76 (5.49:12.6)^{E}+7
Cabonga	426.5	165.6 (154.3:179.5)	5.4 (4.5:6.6)	7.06 (6.58:7.65)^{E}+10	2.32 (1.92:2.80)^{E}+9
Brisay	4378.4	63.0 (51.6:76.1)	0.8 (0.6:1.0)	2.76 (2.26:3.33)^{E}+11	3.49 (2.76:4.38)^{E}+9
Châteauvert	39.4	156.4 (147.6:165.9)	1.4 (1.2:1.7)	6.17 (5.82:6.54)^{E}+9	5.56 (4.64:6.66)^{E}+7
Churchill[a]	5645.2	117.2 (104.7:129.9)	3.9 (3.2:4.7)	6.61 (5.91:7.33)^{E}+11	2.21 (1.82:2.67)^{E}+10
Cinconsine	12.6	161.4 (152.2:172.5)	3.2 (2.6:3.8)	2.03 (1.91:2.17)^{E}+9	3.98 (3.30:4.80)^{E}+7
Manic-5 and 5A	1690.4	118.0 (108.2:130.0)	0.6 (0.5:0.7)	1.99 (1.83:2.20)^{E}+11	1.03 (0.85:1.25)^{E}+9
Dozois	306.7	157.3 (144.9:170.2)	7.2 (5.8:8.9)	4.82 (4.44:5.22)^{E}+10	2.20 (1.77:2.73)^{E}+9

(*continued on next page*)

Table A.4 (*continued*)

Power plant/Water body	Reservoir area (km^2)	Net CO$_2$ emissions (gCO$_2$·m^{-2}·yr^{-1})	Net CH$_4$ emissions (gCH$_4$·m^{-2}·yr^{-1})	Net CO$_2$ emissions (gCO$_2$·yr^{-1})	Net CH$_4$ emissions (gCH$_4$·yr^{-1})
Eastmain-1 and 1A	588.5	46.7 (35.1:59.8)	1.1 (0.8:1.3)	2.75 (2.07:3.52)^{E}+10	6.21 (4.84:7.82)^{E}+8
Sakami	605.6	137.1 (124.1:153.0)	1.4 (1.2:1.7)	8.30 (7.52:9.27)^{E}+10	8.56 (7.15:10.2)^{E}+8
Gouin	1360.6	64.6 (54.1:75.9)	3.6 (2.9:4.4)	8.79 (7.36:10.3)^{E}+10	4.89 (3.96:6.02)^{E}+9
Hart-Jaune	225.4	114.2 (104.7:125.2)	4.7 (3.9:5.7)	2.57 (2.36:2.82)^{E}+10	1.06 (0.87:1.28)^{E}+9
Kempt	181.4	165.0 (153.9:177.8)	5.4 (4.5:6.6)	2.99 (2.79:3.23)^{E}+10	9.87 (8.13:12.0)^{E}+8
La Grande-1	70.9	−21.8 (−27.2: 15.9)	3.6 (2.9:4.4)	−1.55 (−1.93: 1.13)^{E}+9	2.57 (2.04:3.21)^{E}+8
La Grande-2 and Robert-Bourassa	2905.4	145.3 (130.9:160.8)	1.2 (1.0:1.4)	4.22 (3.80:4.67)^{E}+11	3.48 (2.92:4.14)^{E}+9
La Grande-3	2451.9	123.8 (112.2:136.9)	1.1 (0.9:1.3)	3.03 (2.75:3.36)^{E}+11	2.74 (2.31:3.26)^{E}+9
La Grande-4	835.8	105.5 (94.7:116.1)	0.9 (0.7:1.1)	8.82 (7.92:9.71)^{E}+10	7.49 (6.22:9.01)^{E}+8
Toulnustouc	255.1	110.8 (101.9:121.0)	0.6 (0.5:0.7)	2.83 (2.60:3.09)^{E}+10	1.51 (1.24:1.83)^{E}+8
Laforge-1	1240.2	113.6 (103.1:125.1)	1.5 (1.3:1.8)	1.41 (1.28:1.55)^{E}+11	1.90 (1.59:2.27)^{E}+9
Laforge-2	345.9	98.8 (89.9:109.0)	3.7 (3.1:4.4)	3.42 (3.11:3.77)^{E}+10	1.28 (1.08:1.52)^{E}+9
Manic-2	119.9	163.9 (154.7:174.8)	5.1 (4.2:6.1)	1.97 (1.86:2.10)^{E}+10	6.12 (5.08:7.36)^{E}+8
Manic-3	220.0	120.6 (110.5:132.2)	4.8 (4.0:5.8)	2.65 (2.43:2.91)^{E}+10	1.07 (0.89:1.28)^{E}+9
Manouane	52.5	156.9 (147.8:167.3)	3.7 (3.1:4.4)	8.23 (7.75:8.77)^{E}+9	1.95 (1.61:2.36)^{E}+8
Manic-1	12.8	80.9 (73.8:89.0)	0.0 (0.0:0.1)	1.03 (0.94 :1.13)^{E}+9	5.39 (−0.46:12.4)^{E}+5
Mékinac	22.9	171.4 (160.4:184.7)	4.1 (3.4:4.9)	3.93 (3.67 :4.23)^{E}+9	9.38 (7.83:11.2)^{E}+7
Mercier	315.7	194.3 (180.4:209.2)	3.8 (3.2:4.6)	6.13 (5.70:6.61)^{E}+10	1.21 (1.00:1.45)^{E}+9
Mitis	18.5	157.0 (147.3:167.8)	1.8 (1.5:2.2)	2.90 (2.72:3.10)^{E}+9	3.40 (2.82:4.10)^{E}+7
Mondonac	24.6	153.7 (144.3:164.1)	13.3 (10.0:17.8)	3.78 (3.55:4.04)^{E}+9	3.28 (2.46:4.39)^{E}+8
Sarcelle	998.3	49.1 (34.9:65.0)	0.6 (0.3:1.0)	4.90 (3.48:6.49)^{E}+10	6.30 (3.11:10.1)^{E}+8
Boyd	124.8	−0.2 (−11.3:12.1)	0.2 (0.1:0.4)	−1.99 (−141:151)^{E}+7	3.10 (1.15:5.42)^{E}+7
Outardes-3	10.9	87.0 (80.4:94.2)	4.8 (4.0:5.9)	9.51 (8.79:10.3)^{E}+8	5.27 (4.32:6.40)^{E}+7
Outardes-4	639.5	116.1 (105.9:127.9)	1.1 (0.9:1.3)	7.42 (6.77:8.18)^{E}+10	6.90 (5.75:8.27)^{E}+8
Rapide-7	223.6	102.1 (90.7:114.3)	7.0 (5.6:8.7)	2.28 (2.03:2.56)^{E}+10	1.56 (1.25:1.95)^{E}+9
Rapide-blanc	80.4	153.1 (144.7:165.2)	7.3 (5.9:9.0)	1.23 (1.16:1.33)^{E}+10	5.88 (4.77:7.42)^{E}+8
Romaine-1	12.6	−66.3 (−73.1: 58.7)	4.5 (3.7:5.5)	−8.33 (−9.18: 7.38)^{E}+8	5.70 (4.66:6.96)^{E}+7
Romaine-2	85.5	100.9 (92.5:109.4)	1.4 (1.2:1.7)	8.63 (7.91:9.35)^{E}+9	1.19 (0.99:1.43)^{E}+8
Romaine-3	38.4	101.1 (93.5:109.8)	1.7 (1.4:2.0)	3.88 (3.59:4.22)^{E}+9	6.39 (5.33:7.65)^{E}+7
Sainte-Marguerite-3	261.3	103.4 (94.9:112.2)	0.7 (0.6:0.8)	2.70 (2.48:2.93)^{E}+10	1.74 (1.44:2.11)^{E}+8
Taureau	98.2	167.4 (156.3:180.8)	7.3 (5.9:9.1)	1.64 (1.53:1.78)^{E}+10	7.20 (5.85:8.91)^{E}+8
TOTAL without Churchill				**2.34 (2.08:2.63)^{E}+12**	**4.06 (3.31:4.96)^{E}+10**

[a] The Churchill reservoir is not owned by Hydro-Québec. It is located in the Newfoundland-Labrador province and most of the electricity produced is bought by Hydro-Québec.

Table A.5
Total reservoir GHG emissions per kWh electricity produced for each hydroelectric complex using the G-res approach

Complex	Power plants	Water bodies	Electricity production 2011–2015 (GWh·yr^{-1})	Net CO$_2$ emissions (gCO$_2$·yr^{-1})	Net CH$_4$ emissions (gCH$_4$·yr^{-1})	Total GHG emissions (gCO$_2$eq·kWh^{-1})
Bersimis	Bersimis-1	Pipmuacan	6156	1.03^{E}+11	3.79^{E}+9	25.0
	Bersimis-2	Betsiamites	3397	6.30^{E}+9	2.78^{E}+7	
Eastmain	Eastmain-1 and 1-A	Eastmain-1	5744	2.75^{E}+10	6.21^{E}+8	24.2
		Rupert upstream		2.19^{E}+10	3.31^{E}+8	
		Rupert downstream		−6.59^{E}+8	8.76^{E}+7	
	Sarcelle	Opinaca	631	4.90^{E}+10	6.30^{E}+8	
La Grande	Brisay	Caniapiscau	1988	2.76^{E}+11	3.49^{E}+9	20.1
	Laforge-1	Laforge-1	4104	1.41^{E}+11	1.90^{E}+9	
	Laforge-2	Laforge-2	1657	3.42^{E}+10	1.28^{E}+9	
	La Grande-1	La Grande	8381	−1.55^{E}+9	2.57^{E}+8	
	La Grande-2-A and Robert-Bourassa	Robert-Bourassa	43142	4.22^{E}+11	3.48^{E}+9	
	La Grande-3	La Grande-3	12913	3.03^{E}+11	2.74^{E}+9	
	La Grande-4	La Grande-4	14122	8.82^{E}+10	7.49^{E}+8	
		Boyd		−1.99^{E}+7	3.10^{E}+7	
		Sakami		8.30^{E}+10	8.56^{E}+8	
Manic	Manic-1 and McCormick	Manicouagan	2632	1.03^{E}+9	5.39^{E}+5	19.1
	Manic-2 (Jean-Lesage)	Manic-2	5402	1.97^{E}+10	6.12^{E}+8	
	Manic-3 (René-Lévesque)	Manic-3	5266	2.65^{E}+10	1.07^{E}+9	
	Manic-5 and 5-PA	Manicouagan	6621	1.99^{E}+11	1.03^{E}+9	
	Hart-Jaune	Petit lac Manicouagan	244.8	2.57^{E}+10	1.06^{E}+9	
	Toulnustouc	Lac Sainte-Anne	2534	2.83^{E}+10	1.51^{E}+8	
Outardes	Outardes-2	Outardes	2529.7			9.8
	Outardes-3	Outardes-3	4279	9.51^{E}+8	5.27^{E}+7	
	Outardes-4	Outardes-4	3395	7.42^{E}+10	6.90^{E}+8	
St-Maurice		Châteauvert		6.17^{E}+9	5.56^{E}+7	37.9
		Cinconsine		2.03^{E}+9	3.98^{E}+7	

(*continued on next page*)

Table A.5 (*continued*)

Complex	Power plants	Water bodies	Electricity production 2011–2015 (GWh·yr^{-1})	Net CO_2 emissions ($gCO_2 \cdot yr^{-1}$)	Net CH_4 emissions ($gCH_4 \cdot yr^{-1}$)	Total GHG emissions ($gCO_2eq \cdot kWh^{-1}$)
		Gouin		8.79^{E}+10	4.89^{E}+9	
		Kempt		2.99^{E}+10	9.87^{E}+8	
		Manouane		8.23^{E}+9	1.95^{E}+8	
		Mékinac		3.93^{E}+9	9.38^{E}+7	
		Mondonac		3.78^{E}+9	3.28^{E}+8	
	Rapide-Blanc	Blanc	957	1.23^{E}+10	5.88^{E}+8	
	Beaumont	Saint-Maurice	1389.4			
	Chute-Allard	Saint-Maurice	380.1			
	Grand-Mère	Saint-Maurice	66.6			
	La Gabelle	Saint-Maurice	771.7			
	La Tuque	Saint-Maurice	1391.8			
	Rapides-des-Coeurs	Saint-Maurice	513.1			
	Rocher-de-Grand-Mère	Saint-Maurice	1216.9			
	Saint-Narcisse	Batiscan	113.6			
	Shawinigan-2	Saint-Maurice	1052.4			
	Shawinigan-3	Saint-Maurice	1071.9			
	Trenche	Saint-Maurice	1582.6			
Romaine	Romaine-1	Romaine-1	1225.4	−8.33^{E}+8	5.70^{E}+7	3.8
	Romaine-2	Romaine-2	2798.2	8.63^{E}+9	1.19^{E}+8	
	Romaine-3	Romaine-3	1260.2	3.88^{E}+9	6.39^{E}+7	
Outaouais (inferior)	Mercier	Baskatong	267	6.13^{E}+10	1.21^{E}+9	73.2
		Cabonga		7.06^{E}+10	2.32^{E}+9	
		Dozois		4.82^{E}+10	2.20^{E}+9	
	Bryson	Outaouais	366.5			
	Carillon	Outaouais	2535.4			
	Chelsea	Gatineau	781.4			
	Chute-Bell	Rouge	1.1			
	Chute-des-Chats	Outaouais	571.9			
	Hull-2	Outaouais	127.5			
	Paugan	Gatineau	NA			
	Rapides-Farmer	Gatineau	468.5			
Outaouais (superior)	Rapide-7	Decelles	310.6	2.28^{E}+10	1.56^{E}+9	28.6
	Rapide-2	Outaouais	324.8			
	Première-Chute	Outaouais	636.4			
	Rapides-des-Quinze	Outaouais	607.7			
	Rapides-des-Îles	Outaouais	768.4			
Saint-Laurent	Beauharnois	Saint-Laurent	12180.3			0
	Les Cèdres	Saint-Laurent	391.2			
	Rivière-des-Prairies	Rivière-des-Prairies	264.7			
Saint-François	Chute-Hemmings	Saint-François	123.4			0
	Drummondville	Saint-François	58.9			
Sainte-Marguerite	Sainte-Marguerite-3	Sainte-Marguerite-3	2608	2.70^{E}+10	1.74^{E}+8	12.6
Mitis	Mitis-1 and Mitis-2	Mitis	57.6	2.90^{E}+9	2.40^{E}+7	64.5
Péribonka	Péribonka	Péribonka	2592.6			0
Sainte-Anne	Sept-Chutes	Sainte-Anne	88.9			0

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