NTNU
Norwegian University of
Science and Technology

Greenhouse gas emissions from fresh water reservoirs

Pranab Raj Dhakal

Hydropower Development
Submission date: June 2018
Supervisor: Oddbjørn Bruland, IBM
Co-supervisor: Atle Harby, SINTEF Energy Research AS

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering

NTNU

Agreement concerning MSc theses and supervision

This Agreement confirms that the topic for the MSc thesisis approved, the supervisory issues are agreed and the parties to this Agreement (student, supervisor and department) understand and accept the guidelines for MSc theses. This Agreement is also subject to Norwegian law, the examination regulations at NTNU, the supplementary provisions and the regulations for the MSc Engineering Education programme.

1. Personal information

Family name, first name: **Dhakal, Pranab Raj**	Date of birth **March 16, 1992**
Email address **pranabd@stud.ntnu.no**	Phone

2. Department and programme of study

Faculty **Faculty of Engineering**
Department **Department of Civil and Environmental Engineering**
Programme of study **Hydropower Development**

3. Duration of agreement

Starting date **January 15, 2018**	Submission deadline* **June 11, 2018**
If part-time study is approved, state percentage:	

* *Including 1 week extra for Easter*
All supervision must be completed within the duration of the agreement.

4. Thesis working title

Greenhouse gas emissions from fresh water reservoirs

5. Supervision

Supervisor **Oddbjørn Bruland**
Co-supervisor: **Atle Harby** (SINTEF Energy Research AS)

Standardized supervision time is **25 hours** for 30 credits (siv.ing) and **50 hours** for 60 credits (MST) theses.

6. Thematic description

Perform a literature review and describe the process and challenges of evaluating greenhouse gas emissions from freshwater reservoirs with focus on hydropower reservoirs.
Get familiar with the G-Res Tool (https://www.hydropower.org/topics/technical/gres) for calculating GHG emissions from reservoirs.
Use the G-Res Tool to calculate emissions from selected reservoirs where SINTEF has collected data: Follsjø and Svartevassmagasinet in Norway, Nam Gnouang in Laos, Banje in Albania. Compare results from G-Res Tool and
measurements.
Use the G-Res Tool to calculate GHG emissions from hydropower reservoirs in Norway. The G-Res Tool is linked to the gRand database where information on large reservoirs can be found. Select all reservoirs in Norway from gRand database and calculate average, median, min and max GHG emissions from Norwegian hydro reservoirs. Discuss the results in relation to other energy sources.

7. Other Agreements

Supplementary agreement	**Not applicable**
Approval required (REK, NSD)	**Not applicable**
Risk assessment (HES) done	**Not applicable**

Appendix (list)

Master Degree Thesis Spring 2018 Pranab Raj Dhakal

8. Signatures

Conditions	Date	Signatures
I have read and accept the guidelines for MSc theses		Student
I take the responsibility for the supervision of the student in accordance with the guidelines or MSc theses	12.02.2018	[signature] Supervisor
I take the responsibility for the co-supervision of the student in accordance with the guidelines for MSc theses	13.02.2018	[signature] Co-supervisor
Department/Faculty approves the plan for the MSc thesis		Department/Faculty

NTNU
Faculty of Engineering Science and Technology
Institute of Civil and Environmental Engineering

MASTER DEGREE THESIS

Spring 2018
for

Student: Pranab Raj Dhakal

Greenhouse gas emissions from freshwater reservoirs

BACKGROUND

Freshwater reservoirs are used to regulate flow for water supply, irrigation, navigation and hydropower. The surface areas of these water bodies and several flux rate measurements indicate that the emission of carbon dioxide ($C0_2$) and methane (CH_4) are relevant to global inventories of greenhouse gas fluxes, but there is insufficient information and tools to support sound decisions about existing and new reservoirs and the possible mitigation measures.

In order to quantify the net greenhouse gas (GHG) emissions from a reservoir, it is necessary to study emissions before and after the construction of the reservoir, as well as emissions due to unrelated anthropogenic sources (UAS). The difference between pre- and post-reservoir emissions from the whole river basin, subtracting the UAS, will be the true net GHG emission.

SINTEF Energi has conducted measurements of pre- and post-impoundment emissions of GHG from hydropower reservoirs in Norway, Albania and Laos. These data will be available for analysis.

IHA has hosted the development of a tool to calculate GHG emissions reservoirs, the G-Res Tool (https://www.hydropower.org/topics/technical/gres).

TASK

The main task is in cooperation with SINTEF to calculate greenhouse gas emissions from selected reservoirs in Norway, Laos and Albania using the G-Res tool and compare this to observations.

Task description

The Master thesis will include:

1. Perform a literature review and describe the process and challenges of evaluating greenhouse gas emissions from freshwater reservoirs with focus on hydropower reservoirs
2. Get familiar with the G-Res Tool (https://www.hydropower.org/topics/technical/gres) for calculating GHG emissions from reservoirs
3. Use the G-Res Tool to calculate emissions from selected reservoirs where SINTEF has collected data: Follsjø and Svartevassmagasinet in Norway, Nam Gnouang in Laos, Banje in Albania. Compare results from G-Res Tool and measurements
4. Use the G-Res Tool to calculate GHG emissions from hydropower reservoirs in Norway. The G-Res Tool is linked to the gRand database where information on large reservoirs can be found. Select all reservoirs in Norway from gRand database and calculate average, median, min and max GHG emissions from Norwegian hydro reservoirs. Discuss the results in relation to other energy sources

Objective and purpose
Document G-Res ability to calculate greenhouse gas (GHG) emissions from reservoirs and compare GHG emissions from Hydropower reservoirs in Norway with estimated GHG emissions from other energy sources.

Subtasks and research questions
Litterature review, summarizing methodologies for GHG emission calculation and GHG emissions from different energy sources including how uncertainties in methodologies and estimates are handled and documented
Modelling of greenhouse gas emissions using G-Res.
Analyzing and discussion of methodology and results i relation to literature findings including discussion on uncertainties.

Research question: Evaluation of GHG emission estimates as a basis for comparing GHG emissions between energy sources.

General about content, work and presentation

The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:
- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords.(template on: wiki page for students at CEE Departement)
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- The main text.
- Text of the Thesis (these pages) signed by professor in charge as Attachment 1.

The thesis can as an alternative be made as a scientific article for international publication, when this is agreed upon by the Professor in charge. Such a report will include the same points as given above, but where the main text includes both the scientific article and a process report.

Advice and guidelines for writing of the report is given in “Writing Reports” by Øivind Arntsen, and in the departments “Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave” (In Norwegian) located at wiki page for students at CEE Departement

Submission procedure
Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the printed paper to the department office 2-4 days later. The department will pay for 3 copies, of which the institute retains two copies. Additional copies must be paid for by the candidate / external partner.

The master thesis will not be registered as delivered until the student has delivered the submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services (Building Safety) of SB II has signed the form. The submission form including the appropriate signatures must be signed by the department office before the form is delivered Faculty Office.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description is to be developed, if and when applicable. See wiki page for students at CEE Departement for agreement forms.

Health, environment and safety (HSE) http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". NTNU student HSE policy is fonud here: https://innsida.ntnu.no/hms-for-studenter

If you are doing labwork for your project og master thesis, you have to take an online e-course in lab HSE. To get link, email kontakt@ibm.ntnu.no.

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Startup and submission deadlines
Startup and submission deadlines are according t o information found in DAIM.

Professor in charge: Oddbjørn Bruland

Other supervisors: Atle Harby

Department of Civil and Transport Engineering, NTNU
Date: 12.02.2018, (revised: dd.mm.yyyy)

____
Professor in charge (signature)

Abstract

Different sources has been used for the production of energy and each of them have their own carbon footprint. Hydropower is a renewable source of energy, the hydropower reservoirs are therefore expected to have lower net Greenhouse Gas (GHG) emission in comparison with non-renewable sources like coal and gas. Hydropower reservoirs have wide range of emissions based on various factors such as climate zone, soil carbon content, reservoir depth, Global Mean Horizontal Radiance, etc. In this report, the annual gross emission from the Norwegian reservoirs is calculated and it is $536*10^3$ tonnes per year. The average GHG emission intensity in Norway is 3.8 g CO_2eqv/ kWh. In addition, the GHG Reservoir (G-Res) tool was used to calculate the emissions from Follsjø and Svartevatn reservoirs in Norway, Banja reservoir in Albania and Nam Gnouang reservoir in Laos. The result from the G-Res tool was compared with the field measurement results done by SINTEF. It is recommended that the G-Res tool develops an emission curve for the lifetime of the reservoir along with the information of average annual GHG emission that it generates now. It is further recommended to develop a factor of correction for field emission measurement just after the spring ice-breakage. A research on the soil carbon content of impoundment under the reservoir would be very helpful to calculate GHG emissions. Finally, the stakeholders of hydropower industries are recommended to invest in the field of relevant industrial research, and on the quantification of the GHG emission from the reservoirs to enhance competitiveness of the hydropower industry in terms of GHG emission intensity per KWh against other sources of energy.

Acknowledgements

This report was written based on master thesis conducted in the spring semester 2017. I would like to express my sincere gratitude to all those persons and organizations (mentioned and unmentioned) whose valuable support and suggestions have helped to complete this research work in the present shape. Infact, I received guidance, support, encouragement, suggestions, necessary information and valuable ideas from different people and organizations.

First, I would like to thank my supervisor(s) Mr. Atle Harby (SINTEF Energi AS) and Prof. Oddbjørn Bruland (NTNU) for providing research materials, guidance, comments and recommendations, which were very valuable. Secondly, I would also like to thank IHA (International Hydropower Association), other organizations and developers of the GHG Reservoir (G-Res) tool for letting me simulate the greenhouse gas emission through it.

I would in addition like to thank Mr. Håkon Sundt (NTNU), Prof. Knut Alfredsen (NTNU), Prof. Leif Lia (NTNU) for their invaluable support in the retrieving of data and information needed for the project. The online tools developed by NVE (NVEatlas, NEVINA) and the information provided by them readily was very helpful.

Last but not the least, I would like to thank the Department of Civil and Environmental Engineering for this opportunity to do master thesis and SINTEF Energi AS for the project.

Pranab Raj Dhakal
Trondheim
June 2018

Table of Contents

List of tables

List of figures

Abbreviations and Acronyms

A/V : Area / Volume at HRV

C : Carbon

CH_4 : Methane

CO_2 : Carbon dioxide

e/eqv : equivalents

g : Grams

GHG : Green House Gas

GRanD: Global Reservoir and Dam Database

GWP : Global Warming Potential

G-Res : Greenhouse gas REServoirs

HRV : Highest Regulated Water Level

IPCC : Intergovernmental Panel on Climate Change

km^2 : Squared kilometres

KWh : Klio Watthours

LRV : Lowest Regulated Water Level

m : metres

masl : Metres above sea level

mg : milligrams

m/s : Metres per Second

m^2 : Squared metres

NASA : National Aeronautics and Space Administration

N_2O : Nitrous oxide

Pg : Petagrams

pH : Power of Hydrogen

tCO_2eqv : Tonnes of Carbon dioxide equivalent

TWh : Tera Watthours

UAS : Unrelated Anthropogenic Sources

WNA : World Nuclear Association

yr : Year

^0C : Degree Celsius

1 Introduction

This chapter discusses the chemistry behind the greenhouse emission from the freshwater reservoirs around the world, similarities and differences between reservoirs in different climatic conditions as well. The objectives and limitations of the project and GHG emission intensity of different sources of electricity. It is expected that the readers understand the basic process of carbon cycle occurring in the freshwater reservoirs.

1.1 Background

The earth receives solar energy and this solar energy keeps the average temperature suitable for survival of the living creatures. The temperature is maintained by trapping some of the solar radiation inside the earth's atmosphere. Several gases in the earth's atmosphere play a vital role in this process. The process of trapping solar radiation in the earth's atmosphere with the aid of various gases in the atmosphere is called greenhouse effect. (NASA, 2018) The gases mainly responsible for the greenhouse effect are defined as greenhouse gases. Carbon dioxide (CO_2), nitrous oxide (N_2O) and Methane (CH_4) are the three main greenhouse gases. (Raval & Ramanathan, 1989)

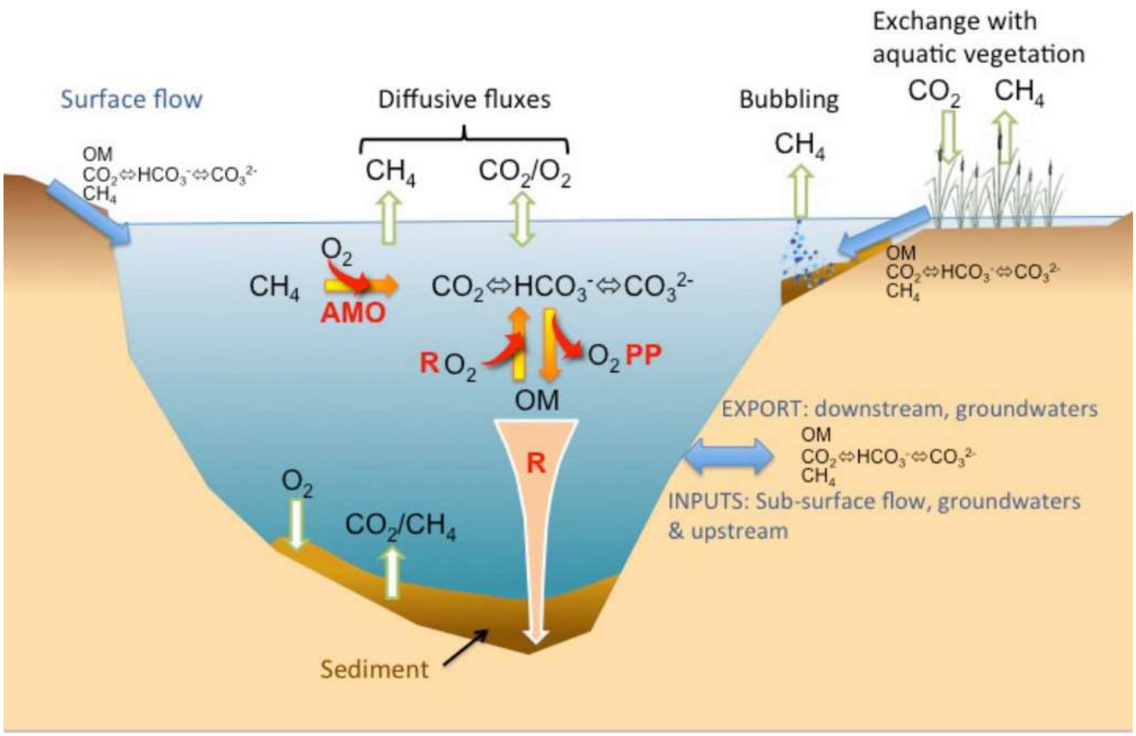


Figure 1.1 Carbon cycle in waterscape (Harby, Guerin, Bastien, & Demarty, 2012)

Since industrialization the use of non-renewable source of energy for fuel has increased the greenhouse gases in the atmosphere because the energy sources such as coal, petrol, diesel, etc.

which were buried under the earth surface are combusted. The combustion of these non-renewable resources has now contributed to the excessive trapping of the solar radiation and the earth's temperature is increasing, leading to a process known as global warming. (Hulme, et al., 1999)

Carbon in the biosphere is unevenly distributed in mainly three storages i.e. in the marine system, the terrestrial system and the atmospheric system. The global carbon cycle is connected between terrestrial and marine systems and finally with atmospheric system by gaseous exchange. It is estimated that the inland water annually receive 1.9 Pg C from the terrestrial landscape, of which 0.2 Pg is buried in aquatic sediments and more than 0.8 Pg is transferred to the atmosphere through gaseous exchange and the remaining 0.9 Pg or less is delivered to the marine carbon reservoir. (Cole, et al., 2007)

The artificial reservoirs bury more organic carbon than the natural lakes. The organic carbon impounded in the reservoirs is 1.5 times more than the organic carbon buried in the ocean. Due to enhanced particle trapping the carbon burial in the early years of impoundment is excessively high. Dean & Gorham estimated the total area of reservoirs is 400,000 km^2 and so the organic carbon buried in reservoirs around the world bury would be 0.16 Pg/yr (Dean & Gorham, 1998). From the estimation of St. Louis and others the estimated reservoir area is 1,500,000 km^2 which would result in the total buried carbon to be 0.6 Pg/yr. (Cole, et al., 2007) (St. Louis, Kelly, Duchemin, Rudd, & Rosenberg, 2000)

Different sources has been used for the production of energy and each of them have their own carbon footprint. Hydropower is a renewable source of energy, the hydropower reservoirs are therefore expected to have lower net Greenhouse Gas (GHG) emission in comparison with non-renewable sources like coal and gas. The organic carbon buried under the reservoir will slowly combust and turn into GHG as shown in the Figure 1.1. The hydropower reservoirs are thus an important source of greenhouse gases (GHGs). However, the quantification, modeling, and management of these emissions are limited by the available data and inconsistent methodological approach (Deemer, et al., 2016). It is therefore important to understand and quantify the degree of the impact of these reservoirs compared to other sources of energy.

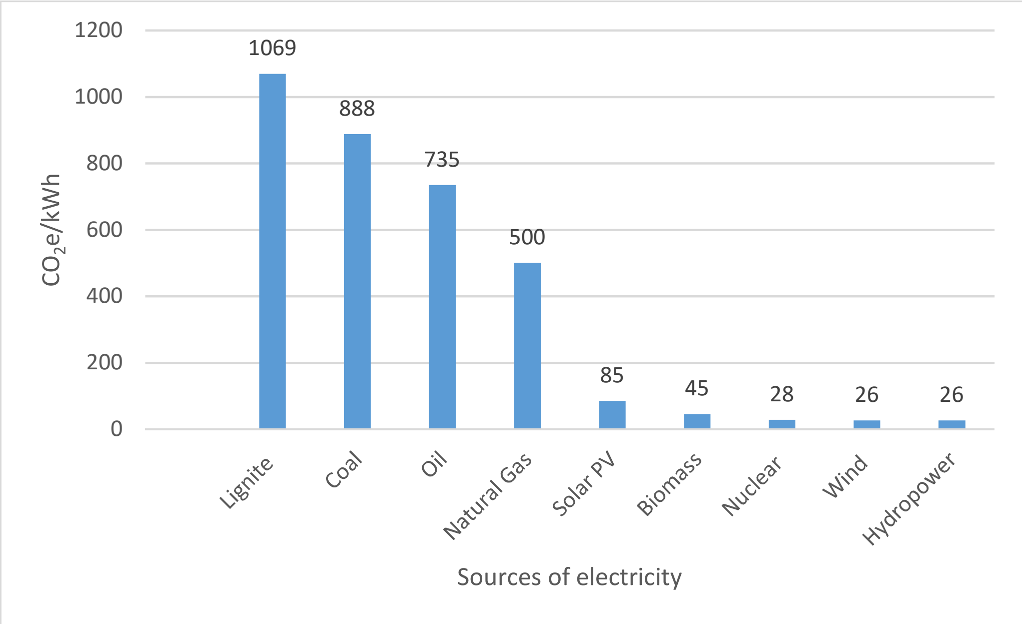


Figure 1.2 GHG emission intensity by sources (WNA, 2011)

The key parameters that affect the GHG emissions are known to be concentrations of dissolved oxygen, water temperature, organic matter concentrations, supply of nutrients and biomass of plants, algae, bacteria and animals in the reservoir. Factors like dam and hydropower operations, water depth, changes in water depth and residence time of water in the reservoir are also very important for the GHG emission status. As all these parameters and factors vary in both time and space, emissions may also show large variations from site to site and from time to time. (Harby, Guerin, Bastien, & Demarty, 2012)

It is found that the flooded organic carbon, water temperature, geographic location of reservoirs, reservoir age, pH value, vegetation and wind velocity influences carbon dioxide emissions from reservoirs. On the other hand reservoir methane emissions are influenced by temperature, water depth, water level, dissolved oxygen, organic carbon, etc. (Yang, et al., 2014) Further, the hydropower reservoirs usually generate less greenhouse gases than natural gas and coal-fired thermoelectric plants. (dos Santos, et al., 2017) (Harby, Guerin, Bastien, & Demarty, 2012) It is said that 75% of the carbon dioxide emission from the reservoirs is natural and this emission would occur in any case. (IHA, 2018)

According to the World Nuclear Association, the average GHG emission intensity of hydropower is 26 CO_2eqv/kWh, which is approximately 20 times lesser than the intensity by natural gas and 28 times lower than the emission intensity of oil. It is also 34 and 41 times lesser than coal and lignite respectively as shown in Figure 1.2 (WNA, 2011) However, the IPCC claims that the median GHG emission from the hydropower reservoirs is 4 CO_2eqv/kWh. (IPCC, 2012)

The study on GHG emission from the reservoir is relatively new and not many literature on it are available and a huge gap of information exists. (Kumar & Sharma, 2016) It is therefore important to find the information about the GHG emission of the hydropower reservoirs.

According to (Statkraft, 2018) 99 % of energy in Norway is produced from hydropower and it contributes to the one-sixth of the total power produced around the world. In Norway 141 TWh of energy is produced by hydropower per annum. (Førsund, 2013). Therefore, it is important to find the intensity of GHG emission worldwide and specially in a country like Norway where hydropower is the contributing to almost all of its energy usage. In this report we will try quantifying and analyzing the emission from the hydropower reservoirs based on the following objectives.

1.2 Objectives

The primary objectives of this study are:

i. To use the G-Res tool to calculate GHG emissions from hydropower reservoirs in Norway.
ii. To calculate the hydropower reservoir GHG emission intensity in Norway.
iii. To use the G-Res Tool to calculate the emissions from selected reservoirs (i.e. Follsjø and Svartevassmagasinet in Norway, Banja in Albania and Nam Gnouang in Laos) where SINTEF has collected data.
iv. To compare the results from G-Res tool and the field measurements of the selected reservoirs.

The secondary objectives of this study are:

i. To get familiar with the G-Res tool (https://www.hydropower.org/gres) for calculating GHG emissions from reservoirs.
ii. To perform literature review and describe the process and challenges of evaluating greenhouse gas emissions from freshwater reservoirs with focus on hydropower reservoirs

1.3 Limitations

i. Several parameters govern the emissions in a reservoir and there is high uncertainty in the emissions.

ii. It is very complicated to quantify the emissions from several reservoirs by developing a relationship in some reservoirs between a few parameters (Soil Carbon, Area/Volume, etc.) to emissions from each of these reservoirs due to the high degree of uncertainty

iii. The soil carbon content value used for analysis and calculation are the average from the reservoirs understudy which might not be the average value of impounded soil carbon in the whole region.

iv. The google earth engine may have overestimated the soil carbon content.

v. The area and number of the reservoirs in each climate zone was estimated.

vi. Some of the selected sites are cascade system but the G-Res tool is not developed for cascade systems.

vii. The N_2O emission is not considered in the analysis and calculation.

2 Definitions, concepts, processes and G-Res tool

2.1 Definitions

2.1.1 Gross emissions

The emission that the natural environment delivers to the atmosphere after the reservoir has been constructed is called gross emission. This definition does not acknowledge the previous occurring emission in the system. (Harby, Guerin, Bastien, & Demarty, 2012)

2.1.2 Net emissions

The net emission however is the total emission that has resulted after the reservoir has been constructed minus emission the area under the reservoir used to emit or would emit minus the emission from Unrelated Anthropogenic Sources (UAS). (Harby, Guerin, Bastien, & Demarty, 2012)

2.1.3 Unrelated Anthropogenic Sources (UAS)

New settlements may start near the new reservoir and nutrients will possibly flow into the reservoir from the household activities. These nutrients mostly Phosphorus (P) contribute to the additional GHGs emission. The nutrient added to the reservoir due to anthropogenic activities is called UAS.

2.1.4 Diffusion

Gases with considerably good water solubility like CO_2 (mole fraction solubility 7.07 x 10^{-4} at $20^{o}C$) and N_2O (mole fraction solubility 5.07 x 10^{-4} at $20^{o}C$) are released to the atmosphere across the air-water interface through diffusion. In other words, soluble gases diffuse to the atmosphere through the air-water interface. (Deemer, et al., 2016)

2.1.5 Ebullition/ Bubbling

Gases with low water solubility such as CH_4 (mole fraction solubility 2.81 x 10^{-5} at $20^{o}C$) are often released to the atmosphere in the form of bubbles also known as ebullition. These bubbles usually rise from the sediments.

2.1.6 Degassing

The concentration of gases in the water decreases after passing through the generating stations and spillways known as degassing. (Deemer, et al., 2016)

2.1.7 CO_2 equivalent:

The global warming potential of a CO_2 molecule is considered as 1 CO_2eqv or 1 CO_2e or simply 1. The global warming potential (GWP) of the other greenhouse gases is defined based on how many times each of these gases have GWP more than a CO_2 molecule. For example, In a 100-year time frame (which is considered by IPCC) a CH_4 has 34 times more GWP than CO_2 and hence CH_4 has GWP of 34 CO_2eqv or 34 CO_2e or simply 34. (Prairie Y. , Alm, Harby, Mercier-Blais, & Nahas, 2017)

2.1.8 Soil carbon content under the impoundment

An area is inundated for the construction of an artificial reservoir. Before flooding the area presumably had various land use and soil carbon. The soil carbon flooded due to the artificial reservoir is known as soil carbon content under the impounded area. It is expressed in Kg of Carbon per unit area (Kg C/m^2).

2.1.9 GHG emission intensity

It is the amount of carbon dioxide equivalent emission per unit production of power. It is denoted by gCO_2eqv/kWh.

2.1.10 Units of emission

2.1.10.1 Areal emission

The areal emission is calculated in ($gCO_2eqv/m^2/yr.$) grams of carbon-dioxide equivalent per squared meters per year.

2.1.10.2 Reservoir-wide emission

The reservoir-wide emissions is calculated in (tCO_2eqv/yr.) tonnes of carbon-dioxide equivalent per year.

2.1.10.3 Total lifetime emission

The total lifetime emission of reservoir is calculated in (tCO_2eqv) tonnes of carbon-dioxide equivalent.

(Prairie Y. , Alm, Harby, Mercier-Blais, & Nahas, 2017)

2.2 Characteristics of reservoir GHGs emission

Factors such as climate, peculiarities of catchment area, age of reservoir, reservoir area, water residence time, soil carbon content, global mean horizontal radiance, etc. play an important role in the rate of greenhouse gas emission.

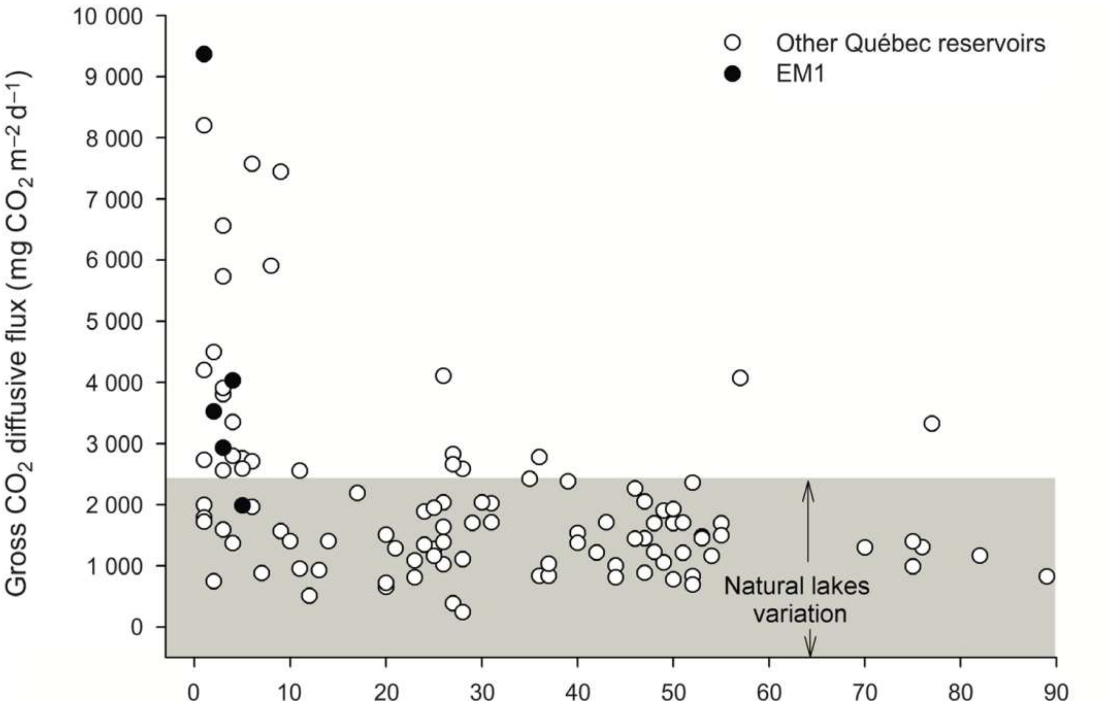


Figure 2.1 Evolution of gross summer CO_2 diffusive emissions per square meter per day with reservoir age (Bastien, Maud, & Tremblay, 2011)

In tropical reservoirs, the gross annual emissions can vary between 87 to 29000 kilotonnes CO_2eqv (Demarty & Bastien, 2011) and the annual boreal and temperate GHGs emission can range from 30 to 1700 kilotonnes CO_2eqv depending on various factors mentioned above. The sub-tropical Nam Ngum reservoir in Lao PDR was found to be carbon sink rather than the source of carbon emission. (Harby, Guerin, Bastien, & Demarty, 2012)

The natural reservoirs release GHGs through diffusion at the surface, bubbling and the vegetation. However, the artificial reservoirs also experience downstream emissions, which includes degassing or diffusive emission in the turbulent waters downstream of the reservoirs, and diffusion and bubbling in river downstream of the power generation station.

The diffusive emissions were recognized first and so are the most studied type of the reservoir emissions. For anoxic gases like methane, it is obvious that bubbling from sediments to the reservoir surface and degassing downstream turbines and spillways are the important emission pathways.

The Figure 2.1 shows a plot of gross summer CO_2 diffusive flux emission (mg CO_2 /m^2 /day) vs age of the reservoirs (years) in Quebec, Canada. In tropical and boreal reservoirs, emissions were usually found to decrease for about 3 to 10 years after the creation of the reservoirs to reach the emission range of the natural lakes. Depending upon the operation of the reservoir, the downstream emission is also observed to decrease with time, but significant emissions can be observed even after two years of flooding. Further, in boreal reservoirs it is interpreted that the gases accumulate under ice and are released as diffusive fluxes on spring ice break-up. The highest emission rates are observed in tropical regions. (Harby, Guerin, Bastien, & Demarty, 2012)

In contrary to the general perseverance that tropical reservoirs release more GHGs than other type of temperate or boreal reservoirs, it is observed that the temperate reservoirs can emit as much methane as the low latitude reservoirs like Amazonian reservoirs. Thus, it is not so easy to generalize the emission rates based on one aspect. (Deemer, et al., 2016)

2.3 On-field measurement of emission

2.3.1 Methods of on-field measurement

There are various methods and techniques used to measure aquatic GHG release in terms of both spatial and temporal aspects as well as different accuracy levels. Measurement of diffusion or diffusive flux has been a primary focus of assessment and some of these can analyze ebullitive emission of methane. Some of these techniques are thin boundary methods, eddy covariance towers, floating chambers, acoustic methods, and funnels etc. (St. Louis, Kelly, Duchemin, Rudd, & Rosenberg, 2000).

The Figure 2.2 shows the various GHG flux measurement techniques which is explained below:

A. **Thin boundary layer method:** In this method diffusive flux is measured by comparing the measured values of the dissolved GHGs with a pre-modeled air-water gas exchange rate.
B. **Eddy covariance technology:** In this method, a tower is erected in a tiny island within the reservoir or in the reservoir and GHGs emission across temporal and spatial range is calculated by using mean air density and instantaneous deviations in vertical wind speed and gas concentrations. It is used to calculate the combined diffusive and ebullitive flux.

Figure 2.2 Various GHG flux measurement techniques (Deemer, et al., 2016)

C. **Floating chambers:** In this method, the floating chamber(s) accumulates diffusive or both diffusive and ebullitive flux over the water surface in air-water interface. The accumulation usually occurs for a short period such as half an hour and the gas accumulated in the close system chamber is used to calibrate and quantify the accumulated GHGs. However, if the instruments for the measurement of gas can be brought to the field it is possible to calibrate emission continuously. Since the same technique is used for calculating two types of emission, the floating chamber with accumulation of both diffusive and ebullitive flux is considered cheaper and easier.
D. **Funnel traps:** In this method, gas bubbles or ebullition is captured in an inverted funnel over a defined period (hours or days in general, sometimes longer) and quantified.

Furthermore, the comparison of gas concentration measured upstream and downstream of power station and spillway yields the degassing flux. The gas concentration in the reservoir can also be used to calculate the diffusion by using theoretical formulae. (Deemer, et al., 2016) (Harby, Guerin, Bastien, & Demarty, 2012) (Goldenfum, 2010)

2.3.2 Challenges for on-field measurement of emission

Various factors influence the emissions of CO_2 and CH_4. It is very difficult to quantify each of them and develop a general pattern for all. First of all the emission of various GHGs starts right from the construction of dam and inundation of areas with various types of land use. CH_4, CO_2

and even N_2O are released from the decomposition of organic deposits depending on the aerobic and anaerobic nature of the process. Microbial fermentation helps decompose organic carbon into CH_4 which takes place in the two steps first by forming of simple organic compounds such as simple organic acid, small molecular alcohols, etc. from carbohydrate, fatty acid and protein available in the sediments of the flooded lands. Finally the methanogens will release CH_4 and CO_2 from the anaerobic decomposition of the mentioned simple organic compounds.

The various factors that influence the CO2 and CH4 emission are described below.

2.3.2.1 Factors influencing CO_2 emissions

A. Spillways and turbine

The turbine intake and spillways are usually placed much lower than the water surface, where the pressure is very high compared to the atmospheric pressure. The CO_2 dissolved with the water is released when passing through the turbines and spillways because of the exposure to comparatively very low pressure environment.

B. Organic matter

The emissions from the reservoir is as we know highly dependent on the amount of organic matter impounded under the reservoir. In areas with land use of forest and peatlands CO_2 and CH_4 emission is very high because of the huge amount of organic soil carbon stored. The emission is very low if the land use was barren before the formation of the dam. It can also be reduced by clearing out the previously existing source of organic carbon such as forest before impoundment.

C. Temperature

The CO_2 emission can be fluctuated upon the fluctuation of the water temperature. Because the CO_2-water solubility and also the decomposition of organic carbon also changes. For e.g. the increased water temperature will increase the CO_2 emission because of the increase in carbon decomposition rate. This could be true in boreal climates with not a lot of algae in the reservoirs, because in reservoirs with a lot of algae the increased temperature might be helpful for CO_2 absorption as the high temperature helps the increase of algae production.

D. pH value

The pH helps in the formation of bicarbonate at the alkaline conditions, which results in the low saturation state of dissolved CO_2 and hence absorbs atmospheric CO_2 and vice-versa. The critical pH values for absorption and emission is expected to be 7.9 to 8.5.

E. Wind speed

The exchange of gas or gas transfer velocity is dependent on the wind speed at the air-water interface. If the wind speed is over 3 m/s it will excite the release of dissolved gases from the water.

F. Reservoir age

The reservoir age plays a vital role in the GHGs emission. A newly constructed reservoir will have much higher emission than an old reservoir due to the excessive release of the nutrients in the inundated areas, high microbial activities and also the quick decomposition of materials such as leaves, litters, etc. This rate is slowly decreased by growth of aquatic plants which absorb CO_2 by photosynthesis and also due to the decrease of impounded organic matter (Barros, et al., 2011) (Tremblay & eds., 2005)

G. Latitude

The impounded soil carbon partially depends on the latitude, for example the tropical regions are expected to have more impoundment than tropical, etc. The temperature also has a significant role in the rate of emission as discussed. Further CO_2 emissions have exponentially negative correlation with latitudes of geographic location of hydropower reservoirs (Barros, et al., 2011)

2.3.2.2 Factors influencing CH_4 emissions

A. Temperature

When organic matter under go anaerobic decomposition due to microbes, CH_4 is released as a byproduct. The temperature has also an important role in the rate of CH_4 formation. The microbial activities increases when the temperature increases. The methanogenic bacteria have high sensitivity to the temperature changes than the methanotrophic bacteria. 25^{o}C is the perfect temperature for CH_4 production. So, if the temperature is in the range of activation of both types of bacteria the emission rate will be high and will be low in the temperature suitable for only one type of bacteria. Thus, the CH_4 production is usually linear or exponential relationship with the temperature of soil or water.

B. Water depth

CH_4 emission usually occurs in shallower lakes than in the deeper lakes. It is because in deeper lakes there are more possibilities of the CH_4 being dissolved due to high pressure or being oxidized while traveling all the way from the bottom to the top of the reservoir, which is not the case in smaller reservoirs. The emission can be different in different depths even within a reservoir. (Juutinen, Alm, Martikainen, & Silvola, 2001)

C. Fluctuation of water level

The drawdown of water in a reservoirs will help in the vegetation growth by absorbing atmospheric CO_2 in the presence of sunlight, this region when later inundated will have anaerobic condition which can be a perfect source for methane production. Methane production has much more adverse effect to the environment than CO_2 production. (Fearnside, 2008)

D. Other factors

In addition to the above factors wind speed, water velocity and air-water temperature difference as well as weather conditions, water quality, water retention time, carbon input to the reservoir from the upstream, the primary production of aquatic plants, etc. also play an important role in the CH_4 emission. (Yang, et al., 2014) (Hällqvist, 2012)

All the factors discussed above and many other factors play a vital role in GHG emission from a reservoir, however the physical, chemical and environmental conditions of any two reservoirs are not at all the same. (Kumar & Sharma, 2016) It is therefore very challenging to develop a general formula that can quantify emission from reservoirs.

G-Res tool has been developed as a simulating tool considering the emission due to many of factors the discussed above.

2.4 G-res tool

G-res tool was developed to address the need of a reliable and consistent approach to map and estimate the reservoir GHG emission. This section discusses only the factors which the G-res tool takes into consideration, the readers are suggested to go through the G-res user guide for detailed information which is available from within the G-res tool and IHA website. It is very important understand that the G-Res tool is not developed for cascade systems and N_2O emissions are not considered in the calculation process of the tool.

"*The G-res tool estimates 'net GHG footprint' from the creation of a reservoir. This approach is based on the recommendation from the Intergovernmental Panel on Climate Change (IPCC, 2011) that net emissions should be evaluated in determining the impact of reservoir systems. Thus, a realistic portrait of the net impact of a reservoir should consider the GHG balance of the pre-impounded area and remove, or add, it to the GHG balance of the reservoir itself post impoundment. In addition, the G-res tool takes into account the possibility that some reservoir emissions could be the result of human activity unrelated to the creation of the reservoir itself needs to be accounted for. The tool further includes the indirect GHG emissions attributed to the manufacture, transportation and installation of reservoir infrastructure construction. This provides a more comprehensive estimation of the overall emissions associated with a reservoir. The calculation of net GHG footprint in the G-res tool is defined by the following equation*."

Net GHG footprint = [Post-impoundment GHG balance of the reservoir] – [Pre-impoundment GHG balance of the reservoir area before its introduction] – [Emissions from the reservoir due to unrelated anthropogenic sources (UAS)] + [GHG due to construction]

The G-res calculates all the values in the right-hand side of the above equation. In doing so, it models GHG emissions using a series of modules, which estimates emissions based on user inputs and calculated parameters based on those inputs. Each of these modules can be summarized as:

2.4.1 Module for emission due to Post-impoundment

"*The GHG balance associated with the reservoir after inundation, which is calculated using a semi-empirical model based on a comprehensive dataset collated from the published peer-reviewed literature on measured GHG fluxes for diffusive, bubbling and degassing emission pathways.*"

2.4.2 Module for emission due to Pre-impoundment

The GHG balance associated with the area subsequently occupied by the reservoir, which is calculated based on the land-cover and a set of emission factors that represents the emission in a land cover at the location of the reservoir.

2.4.3 Module for emission due to Unrelated anthropogenic sources

The GHG emissions that can be attributed to activities within the catchment calculated based on the proportions of sources of nutrients and carbon flowing into the reservoir.

2.4.4 Module for emission due to Construction

The materials for construction of the dam such as steel, concrete, etc. and other infrastructures contribute for emission. More emission can occur due to the need of transportation of construction materials. Different materials have different emission factors.

"*The results for each module are presented in terms of annual emissions, total emissions and areal emissions. Furthermore, the G-res tool includes a methodology for apportioning those emissions to the economic, social and environmental services that the reservoir provides. This provides an indication of the relative contribution to the net GHG impact of each of the services*." (Prairie Y. , Alm, Harby, Mercier-Blais, & Nahas, 2017)

3 Site selection and methods

In this section, the process of site selection and the methods used in the process of calculation are discussed. The analysis and calculation was completely done on computer. First of all the literature review was carried out to understand the process and types of GHGs in the hydropower reservoirs. Various factors influencing the methane and carbon dioxide emissions were studied. The G-Res tool was used to generate the emissions from the reservoirs under study.

3.1 Gross GHG Emissions in Norwegian reservoirs

As discussed in the Background several factors influence the GHGs emission from reservoirs. In this report, a relation of CO_2 and CH_4 emission from reservoirs with respect to total impounded soil carbon per area and area to volume (A/V) ratio at HRV of the reservoirs is respectively is considered as the relationship was clearly seen in our study sites compared to the other factors. The primary aim of the study of gross GHG emission is to find general formulae, the total GHG emission and GHG emission intensity of Norwegian reservoirs.

In this process, more than 60 random reservoirs from around Norway were selected from NVE dataset and studied. 24 of these reservoirs were chosen for analysis based on the availability of various parameters, variability in location, climate zones, altitude, etc. The selection of the reservoirs was done as to develop an equilibrium between the complication arising due to excessive number of reservoirs and under-representation of representative reservoirs from categories of study (altitude, climate zones) under consideration. The initial contract discusses the use of GRanD (Global Reservoir and Dam Database) dataset but in the study NVE dataset is used because the GRanD dataset considers only the reservoirs more than the storage capacity of 0.1 km^3. In considering the reservoirs larger than 0.1 km^3, reservoirs with volume more than 14 km^3 is not considered for studies and the power produced by the discarded plants would be more than 17 TWh. (NVE, 2018), which means a large part of the emission would be missed in the calculation. The other reason to use the NVE online tools are their easy accessibility and user-friendliness.

3.1.1 Selection of reservoirs

3.1.1.1 Based on altitude:

The Norwegian altitude ranges from sea level to 2200 masl. (Senorge, 2018) Four altitude ranges i.e. 0-400, 400-800, 800-1200 and 1200+ masl were taken as the basis of study. The reservoir selection was made as variable as possible so that all the altitude range, varying reservoir volumes, reservoir areas and location were covered as far as possible.

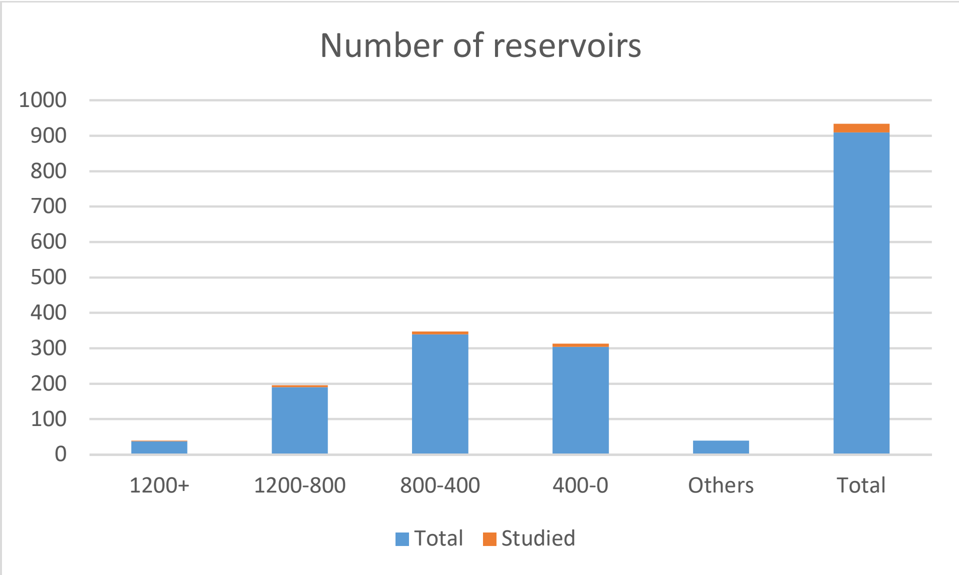


Figure 3.1 Total number of reservoirs in Norway and the studied reservoirs based on altitude (NVE, 2018)

As shown in Figure 3.1, there are 909 reservoirs in Norway and according to the altitude categorization based on LRV only 37 of them are above 1200 masl, 190 lie in the range of 800-1200 masl, 339 lie in the range of 400-800 masl and 304 reservoirs lie in the range of 0-400 masl.

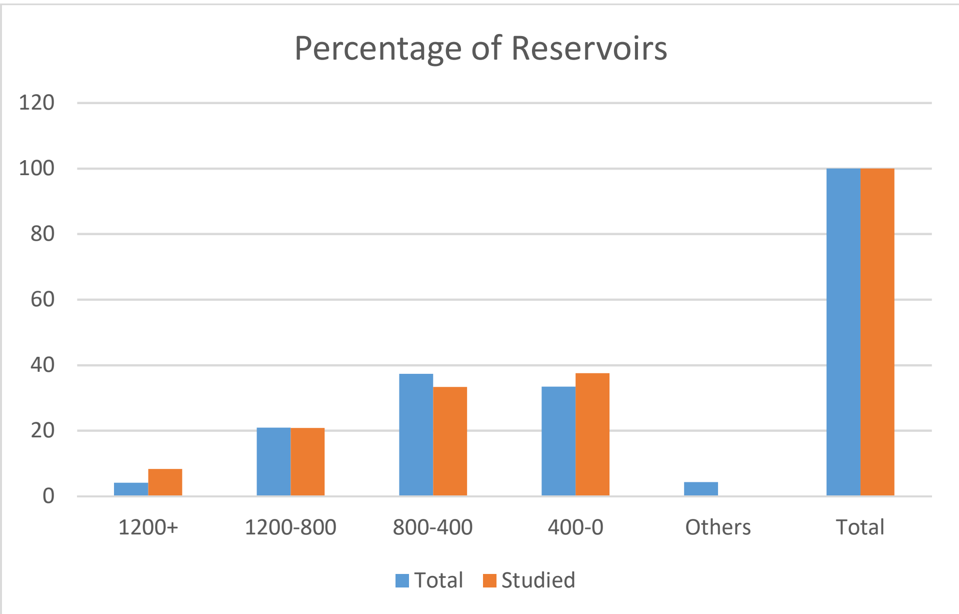


Figure 3.2 Percentage of reservoirs in Norway and studied reservoirs based on LRV altitude (NVE, 2018)

The number of studied reservoirs are 2, 5, 8 and 9 respectively for 1200+ masl, 800-1200 masl, 400-800 masl and 0-400 masl. 38 reservoirs from the data provided by NVE did not have information on the altitude of LRV so these reservoirs are discarded from our study but is considered in the total number of reservoirs and it is acknowledged in our studies as shown in Figure 3.1 and Figure 3.2.

The total percentage of reservoirs in 1200+ masl, 800-1200 masl, 400-800 masl, 0-400 masl and others are respectively 4%, 21%, 37%, 33% and 4%. The studied reservoirs also follow a similar proportion of 8%, 21%, 34% and 37% for 1200+ masl, 800-1200 masl, 400-800 masl and 0-400 masl respectively as shown in Figure 3.2. The category 'others' is discarded in the study. In case of altitude more than 1200 masl, even though studying only one reservoir would be in same proportion to the selected reservoirs compared to the total reservoirs, two reservoirs were selected because it would not be wise to assume the emission value from only one reservoir will represent the emission from the rest of the reservoirs in the group.

3.1.1.2 Based on Climate zones

Norway lies in boreal climate. The climate zones in the country can however be broadly divided into three Köppens climate zones namely Arctic climate, Polar climate and Temperate climate as shown in Figure 3.4.

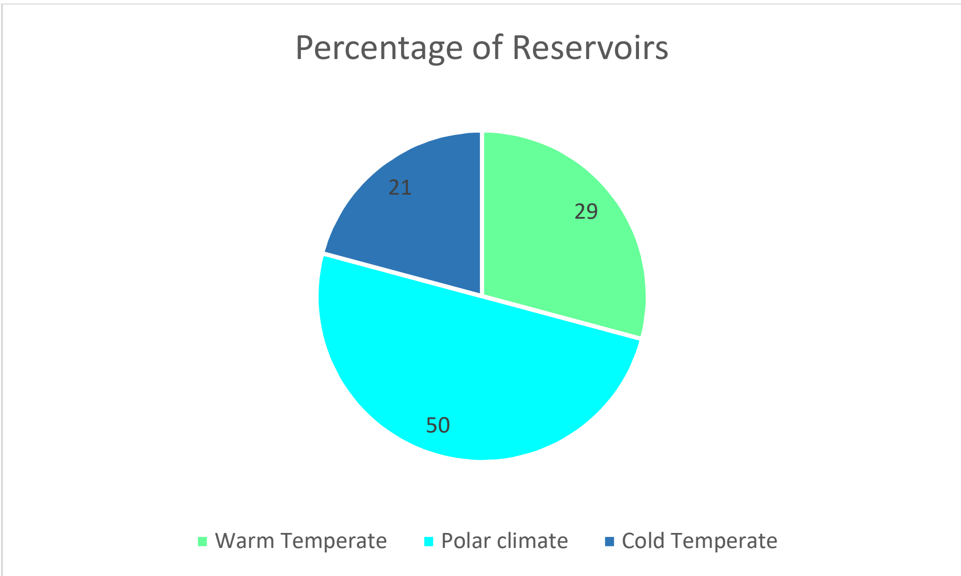


Figure 3.3 Percentage of reservoirs in climate zones (assumed)

Since, in the studies it was decided to follow Figure 3.4 as the map but no GIS or any other information was available from met.no or other sources the reservoir percentage in the different regions were assumed comparing the Figure 3.4 and NVE website for approximate location of reservoirs in different regions. This way 21%, 29% and 50% of the reservoirs were assumed to be in the cold temperate, warm temperate and polar climate respectively and the reservoirs were also selected based on the same assumption which can be seen as a pie-chart in Figure 3.3. It is not expected to have a drastic change in the climate when half of the reservoir is in one climate zone and the other half is in other climate zone due to the presence of grey zone between the two climate zones, so the climate zone considered for the studied dams is the location of the dam.

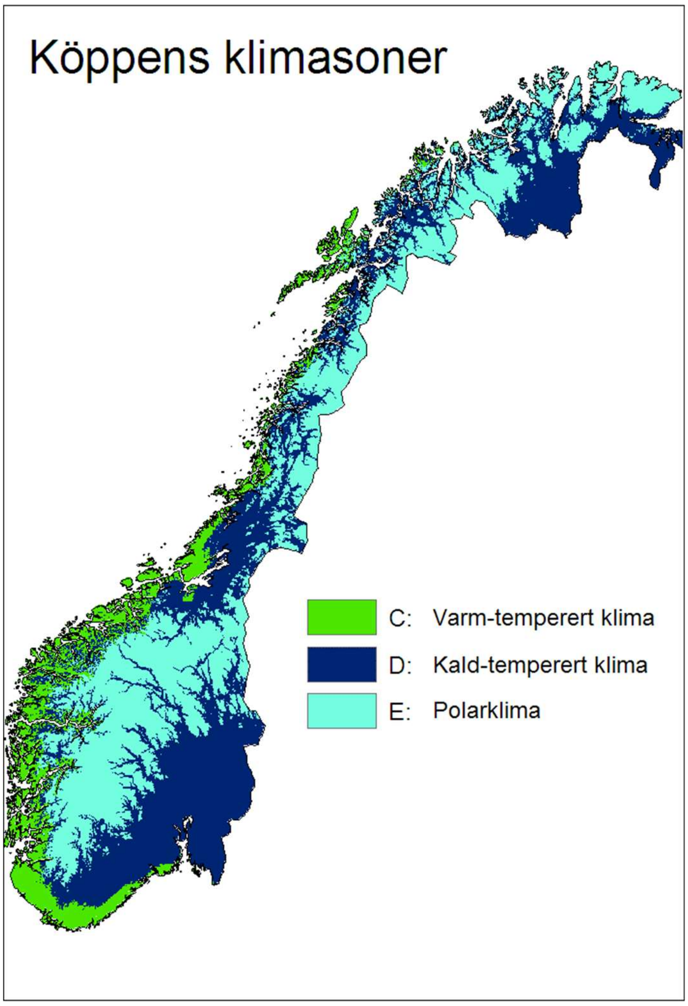


Figure 3.4 Climate zones in Norway (Met.no, 2018)

The Figure 3.5 shows the location of all the reservoirs studied for our analysis. The name of the reservoirs is shown in Table 3.1 and the details of each reservoir is in Appendix. The serial numbers in Table 3.1 are the same as the numbers given for each reservoir in Figure 3.5 and the blue, sky blue and green colours in the background of the Table 3.1 represents the cold temperate, polar and warm temperate climates respectively as shown in Figure 3.4.

Figure 3.5 Location of reservoirs under study (NVE, 2018)

Table 3.1 The selected reservoirs for study

S.No.	1	2	3	4	5	6
Reservoirs	Buevatna	Fuglevatn	Gorningen	Lundevatn	Skarvatn	Spjodevatn/Mjåvatn
S.No.	7	8	9	10	11	12
Reservoirs	Teksdalvatn	Tustervatn-Røsvatn	Altevatn	Follsjø	Gjerdingen	Kalvatn
S.No.	13	14	15	16	17	18
Reservoirs	Nesvatn	Soikkajavrre	Storevatn	Svartevatn	Tussevatn	Blåsjø
S.No.	19	20	21	22	23	24
Reservoirs	Kalhovdmagasinet	Låtervikvatn	Store fjellvatn	Sysenvatn	Isvatn	Kyrkjevatn

3.1.2 Collection of the Data

NEVINA (an online tool developed by NVE) was used to estimate the catchment area, catchment annual runoff, land cover in the catchment area.(NEVINA, 2018) The population in the catchment is assumed to be zero because most of the reservoirs and their catchments in Norway are in the mountainous areas with no or negligible settlements.

The land cover for the pre-impoundment reservoir area was not provided to the G-Res tool because gross emissions are calculated. The latitude and longitude of the dams, reservoir area, reservoir volume, impoundment year were retrieved using NVEatlas (an online tool developed by NVE) (NVE, 2018).

The maximum depth was assumed the highest value between HRV minus LRV (HRV-LRV) and height of the dam. Mean/Normal water intake elevation was the lowest regulated water level plus half the difference of highest and lowest regulated water level and taken as the next whole number. Water intake elevation to the powerhouse was assumed the lowest regulated water level.

Soil Carbon Content under the impounded area, Reservoir mean global horizontal radiance in the reservoir was generated from the Google Earth Engine feature available in the G-Res tool. Wind speed and Temp for the 12 months was calculated from the measuring station nearby with the data available for approximately last 10 years (2007-2016). (eklima, 2018) All the reservoirs have hydroelectricity as the primary purpose of its usage. The GHG emission by the construction materials used in the reservoirs is not considered. The G-Res tool calculated the resulting emission from the inputs.

3.2 Net GHG emissions from four reservoirs around the world

SINTEF Energi AS has done on-field measurement of the GHG emissions in various reservoirs. Floating chambers were used to collect gas during the field measurements. The accumulation of the methane and carbon dioxide in the chamber of known surface and volume is connected to a gas analyzer via tubing for the measurement data. The net GHG emission from four reservoirs, i.e. Follsjøen and Svartevassmagasinet reservoirs in Norway, Banja reservoir in Albania and Nam Gnouang reservoir in Laos is generated from the G-Res tool and compared with the field measurement results by SINTEF.

The catchment area, catchment population, soil cover in the catchment, soil cover under the impounded area, catchment annual runoff is assumed and calculated from various site specific sources available online and also from SINTEF. (see Appendix for data)

The maximum depth was assumed the highest value between HRV minus LRV (HRV-LRV) and height of the dam. Mean/Normal water intake elevation was the lowest regulated water level plus half the difference of highest and lowest regulated water level and taken as the next whole number. Water intake elevation to the powerhouse was assumed the lowest regulated water level.

Soil Carbon Content under the impounded area, Reservoir mean global horizontal radiance in the reservoir was generated from the Google Earth Engine feature available in the G-Res tool.

4 Gross emissions in Norway

Several parameters were input to the G-Res tool and the output was generated. The results presented are based on the input of Global Mean Horizontal Radiance and Global Horizontal Radiance (May to September). This is done to see the difference in total emission every year by consideration of different values in global horizontal radiance.

4.1 Results

4.1.1 Results from Summer Horizontal Radiance as input (Case 1)

Global horizontal radiance for summer (May to September is used) as stated in the user guide and is found from Google Earth Engine.

4.1.1.1 Total emission

a) Carbon dioxide

The CO_2 emission follows the relation of Equation 4-1 with respect to the soil carbon content under the impounded area and R^2 value of 0.9947 as shown in Figure 4.1.

$$y == 10.458x + 14.304 \qquad \textbf{Equation 4-1}$$

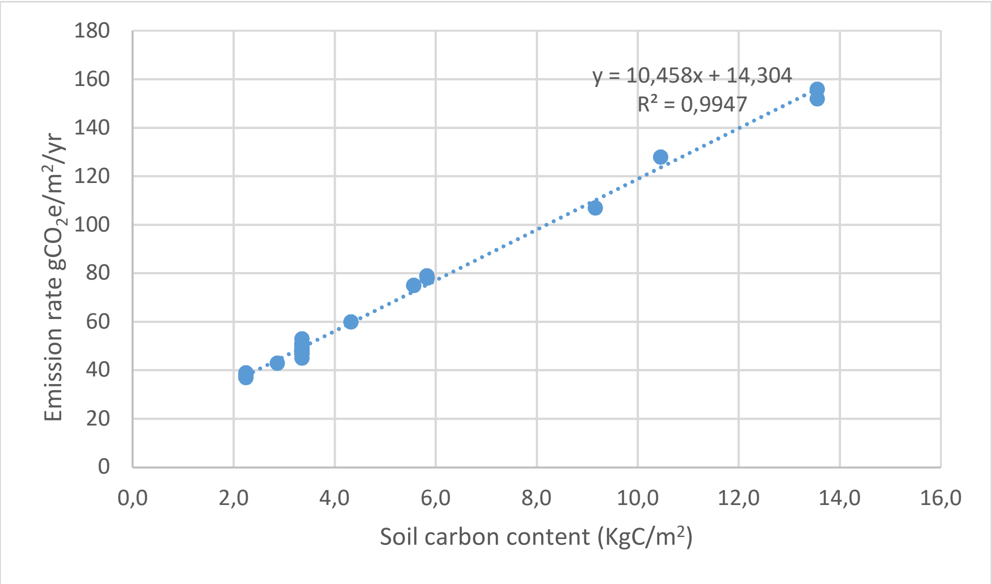


Figure 4.1 The rate of emission vs soil carbon content of a reservoir for CO_2 (Case 1)

b) Methane

The CH_4 emission is found to follow the relation of Equation 4-2 with respect to the ratio of maximum Area to volume of the reservoir and R^2 value of 0.4296 as shown in Figure 4.2.

$$y = 359{,}41x + 2{,}912 \quad \textbf{Equation 4-2}$$

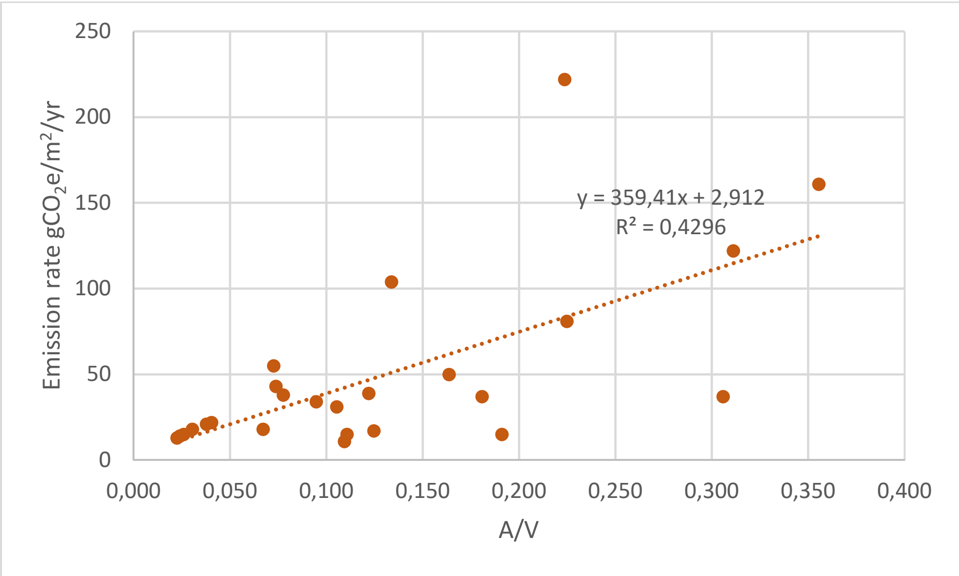


Figure 4.2 The rate of emission vs maximum A/V of a reservoir for CH_4 (Case 1)

4.1.1.2 Emission based on altitude

i. 0-400

a) Carbon dioxide

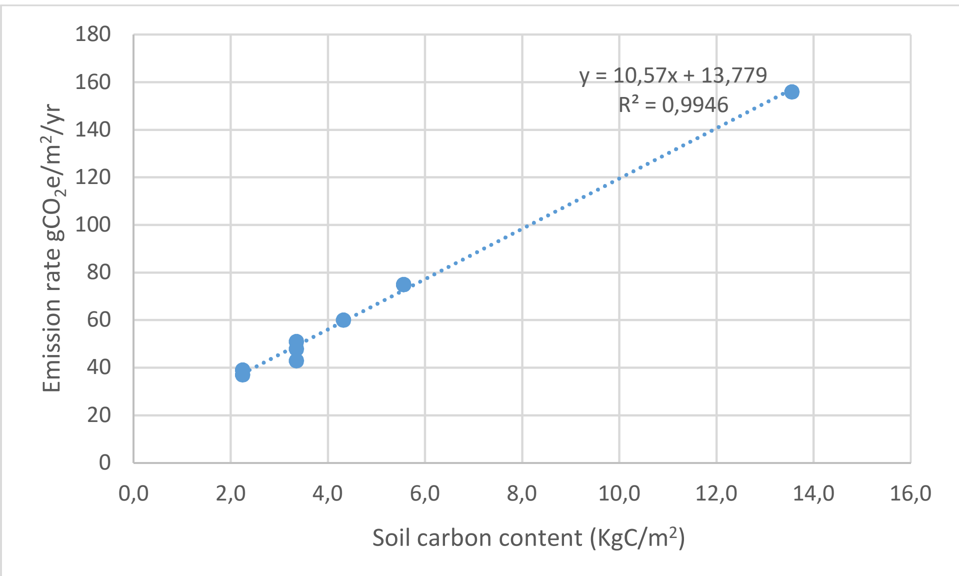


Figure 4.3 Carbon dioxide emission in 0-400 masl

b) Methane

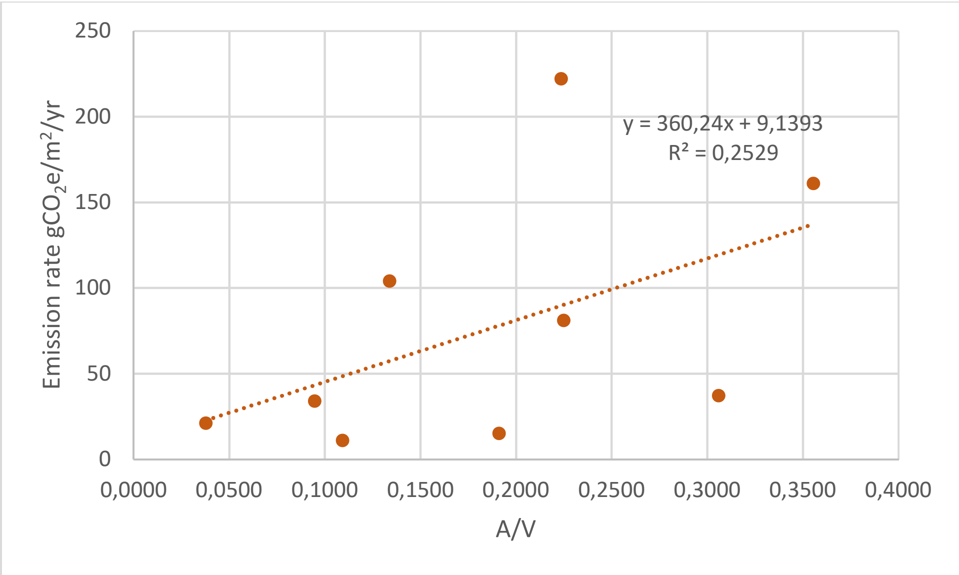


Figure 4.4 Methane emission in 0-400 masl

ii. 400-800

a) Carbon dioxide

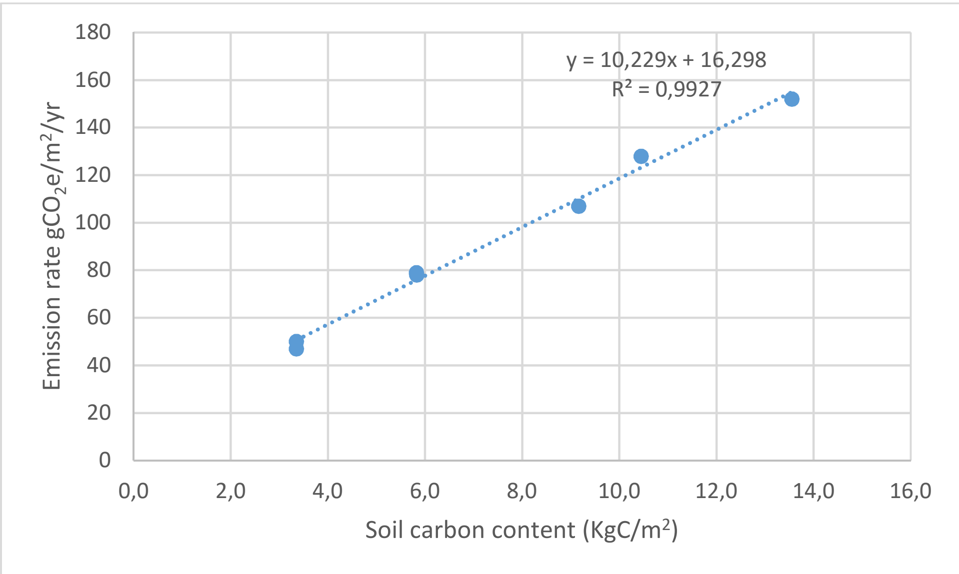


Figure 4.5 Carbon dioxide emission in 400-800 masl

b) Methane

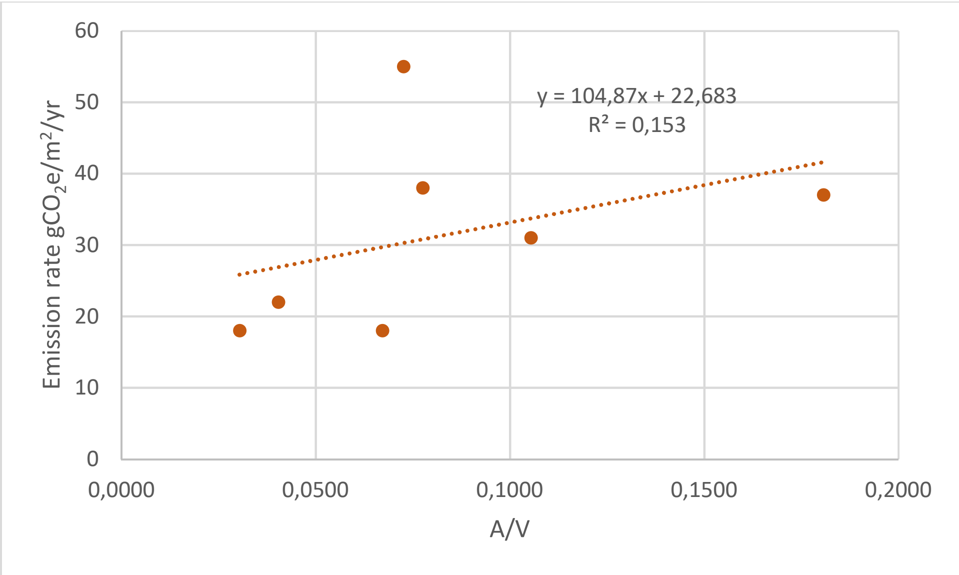


Figure 4.6 Methane emission in 400-800 masl

iii. 800-1200

a) Carbon dioxide

The value of impounded soil carbon per unit area is the same in all the selected reservoirs probably because the region of selection is limited to small area (the area shaded brown is out of the altitude range) as shown in Figure 4.7.

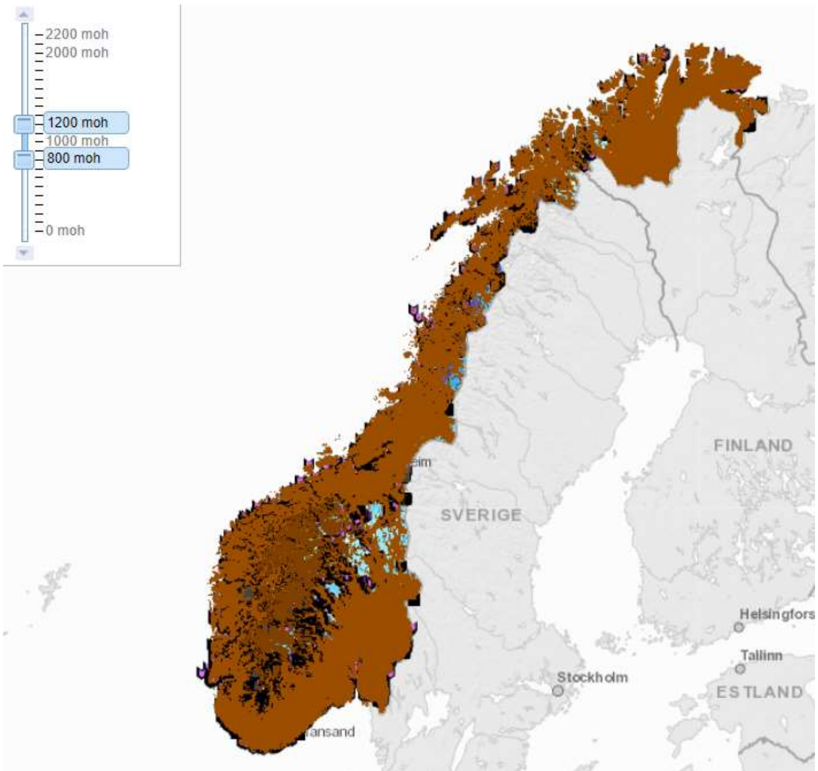


Figure 4.7 The altitude range between 800-1200 masl (Senorge, 2018)

So the average carbon dioxide emission from the studied reservoirs i.e. 49.2 $gCO_2eqv/m^2/yr$ is taken.

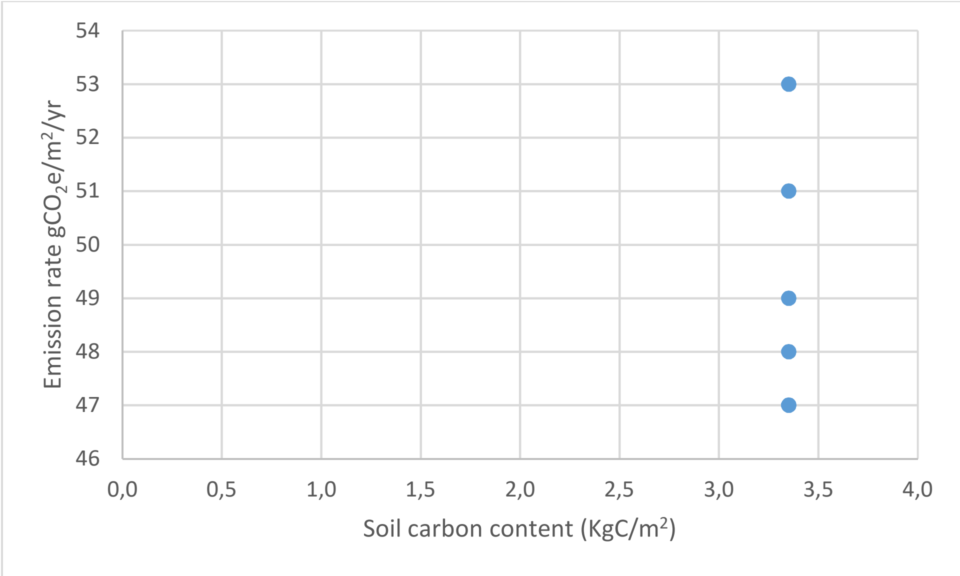


Figure 4.8 Carbon dioxide emission in 800-1200 masl

b) Methane

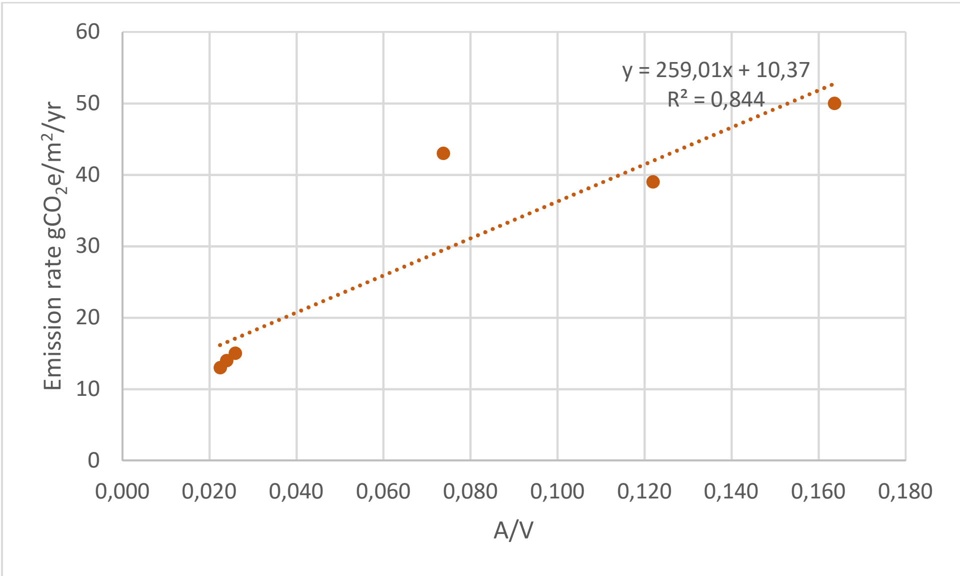


Figure 4.9 Methane emission in 800-1200 masl

iv. 1200-2200

a) Carbon dioxide

Like in the altitude range of 800-1200 masl the soil carbon is same due to limited area occupied by the altitude range as shown in Figure 4.10, where the brown area is not covered in the altitude range of 1200-2200 masl. So the average emission of 46 $gCO_2eqv/m^2/yr$ is considered representative.

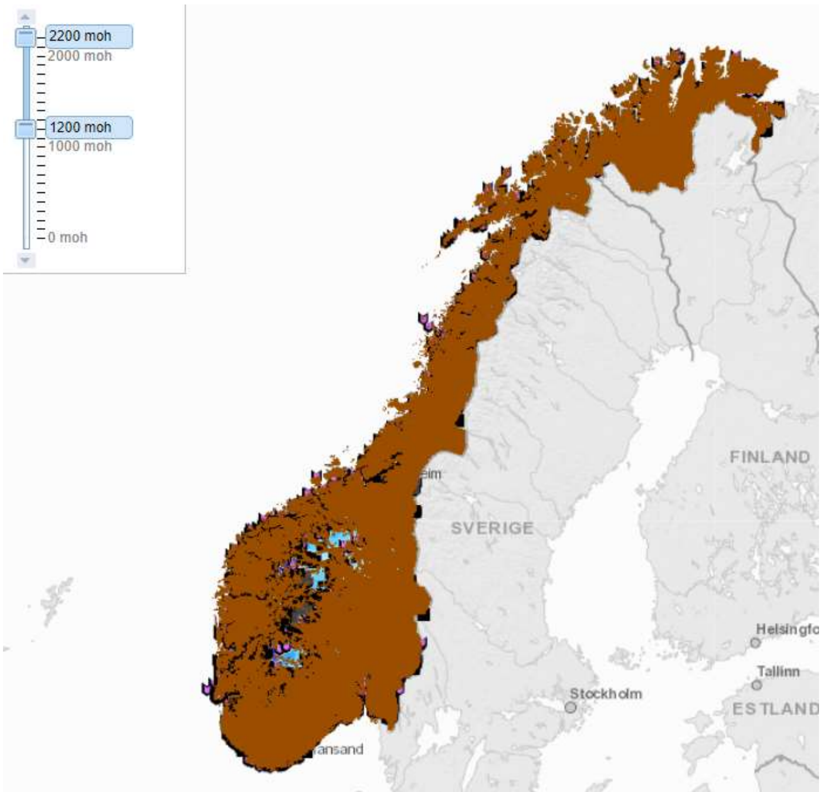


Figure 4.10 The altitude range between 1200-2200 masl (Senorge, 2018)

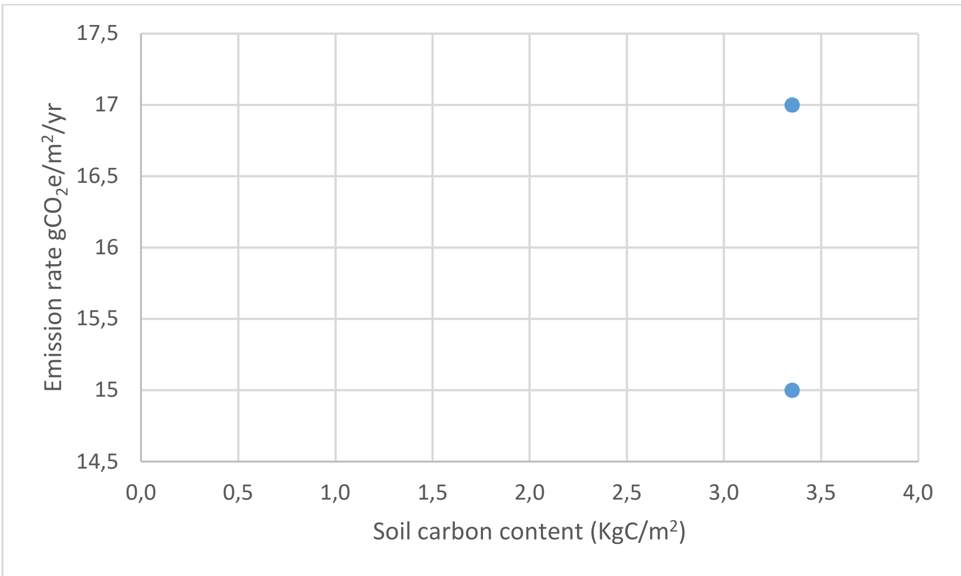


Figure 4.11 Carbon dioxide emission in 1200-2200 masl

b) Methane

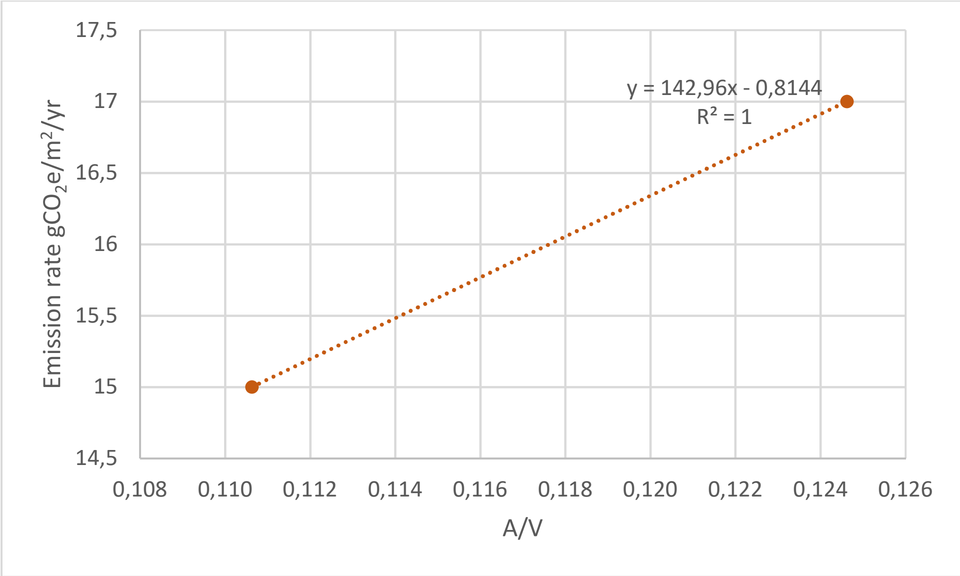


Figure 4.12 Methane emission in 1200-2200 masl

4.1.1.3 Emission based on climate zones

i. Warm temperate

a) Carbon dioxide

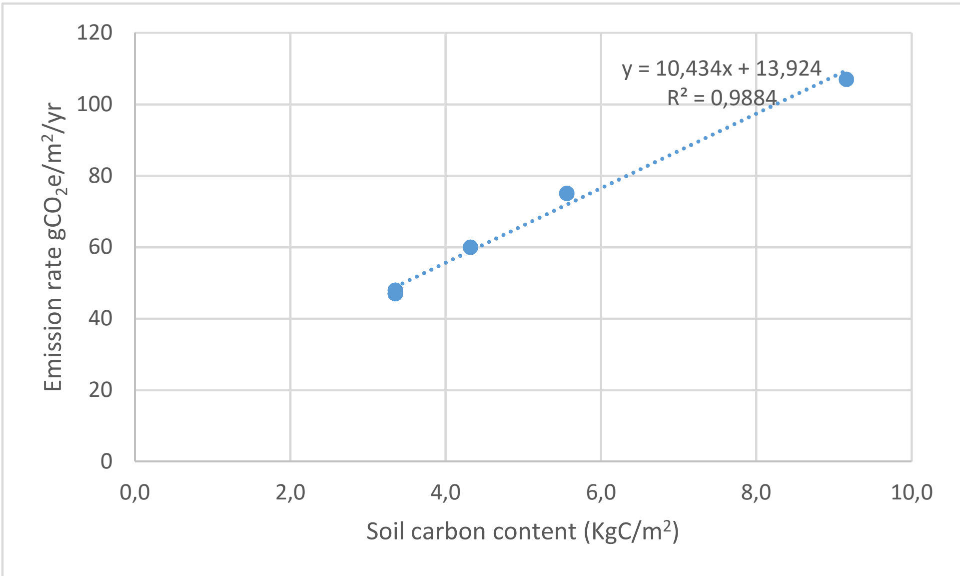


Figure 4.13 Carbon dioxide emission in warm temperate climate zone

b) Methane

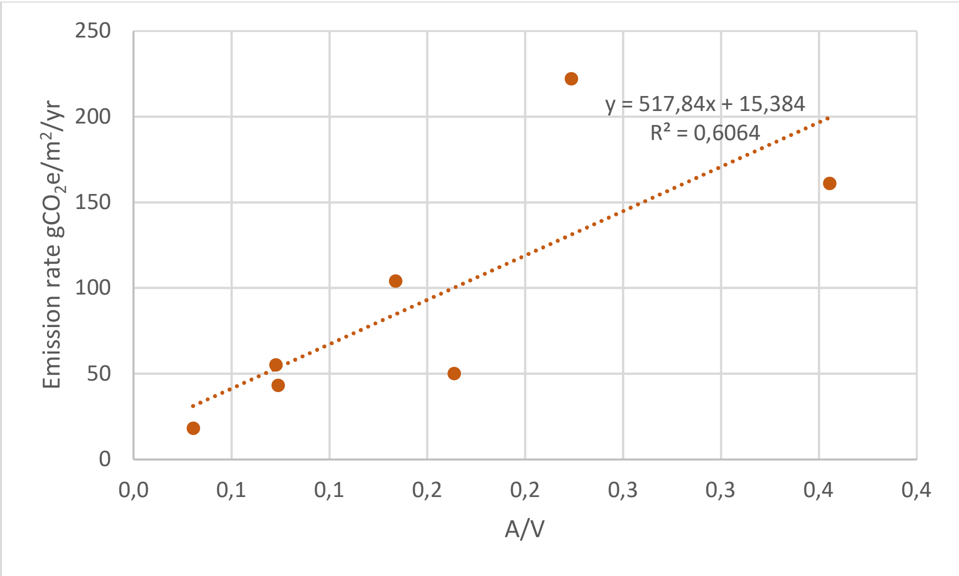


Figure 4.14 Methane emission in warm temperate climate zone

ii. Polar Climate

a) Carbon dioxide

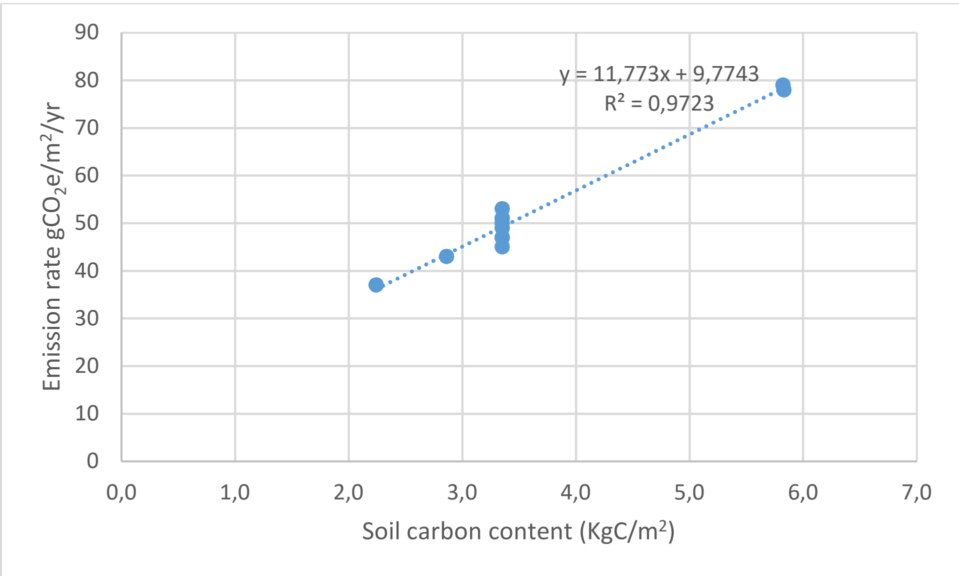


Figure 4.15 Carbon dioxide emission in polar climate zone

b) Methane

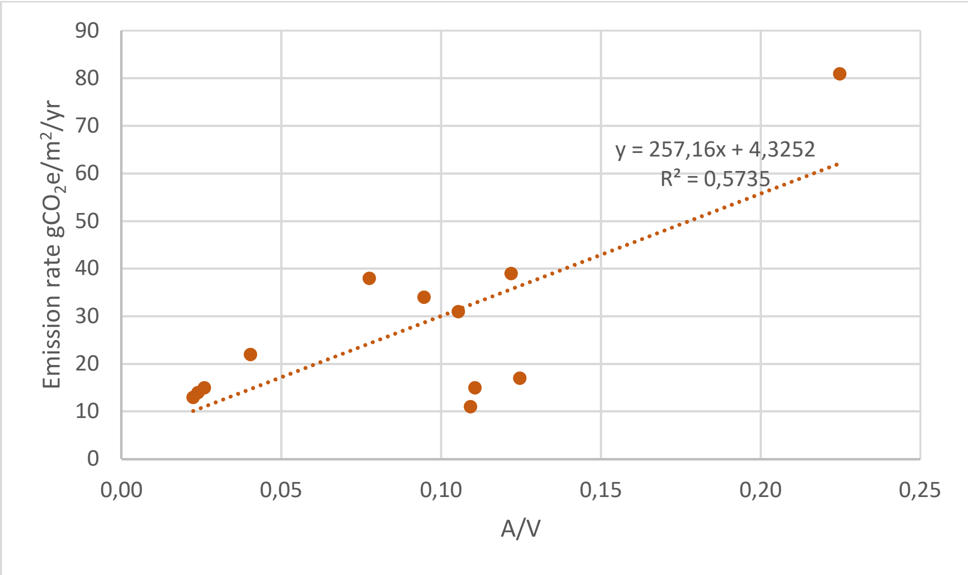


Figure 4.16 Methane emission in warm polar climate zone

iii. Cold temperate

a) Carbon dioxide

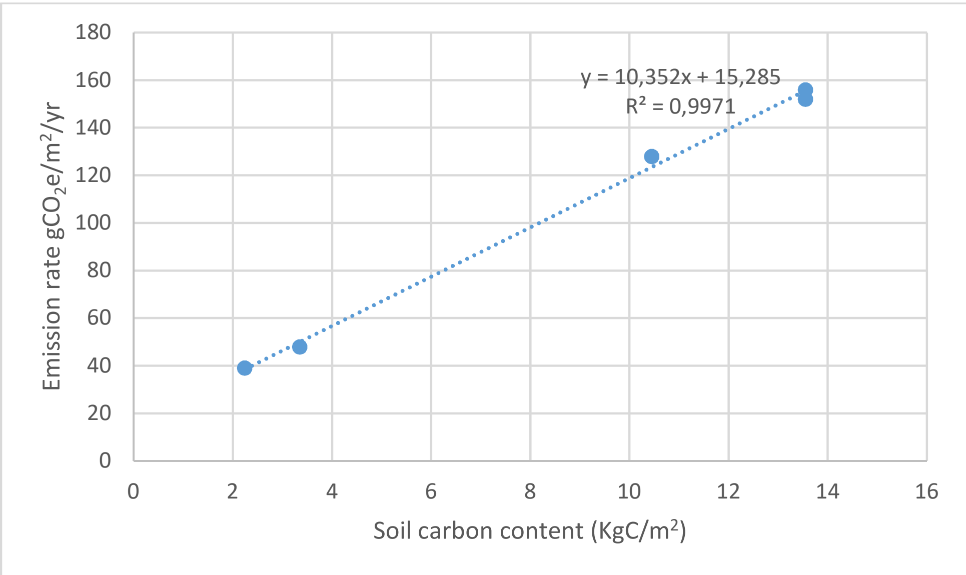


Figure 4.17 Carbon dioxide emission in cold temperate climate zone

b) Methane

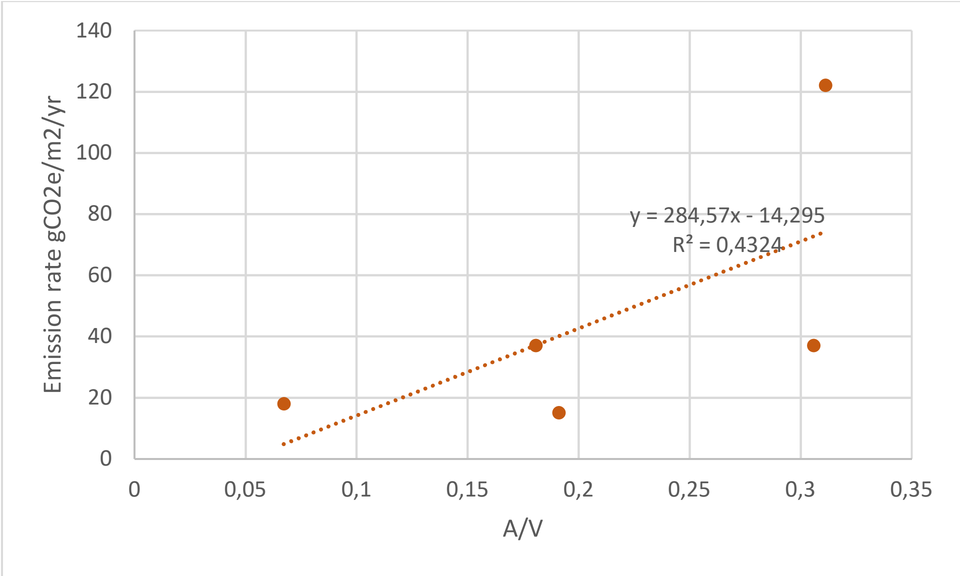


Figure 4.18 Carbon dioxide emission in cold temperate climate zone

4.1.2 Results from Global Mean Horizontal Radiance as input (Case 2)

The graphs and results from the input of Global Mean Horizontal Radiance (Case 2) is provided in the Appendix.

4.2 Summary of emission trends

The Table 4.2 shows the numerical results from the inputs of global mean horizontal radiance and summer (July to September) horizontal radiance as input. It shows that the solar horizontal radiance in general is proportional to the production of methane and the production of carbon dioxide does not in general change with respect to the solar horizontal radiance. The G-Res tool user guide recommends the use of Global Horizontal Radiance (May to September) if the latitude is more than 40ºN (Prairie Y. T., Alm, Harby, Mercier-Blais, & Nahas, 2017) and latitude of Kristiansand, the southernmost city of Norway is about 58ºN (latitudelongitude.org, 2018). Therefore, in the final calculations the results from case 2 is discarded in the Table 4.2 $gCO_2eqv/m^2/yr$ of emission was calculated from the formulae generated in 4.1.1 and 4.1.2 and the results in tonnes per year is calculated by multiplying with the total area of each region. The area for altitude ranges was calculated by adding the area of reservoirs in each altitude range and the total area was also similarly calculated. However, the area of polar, warm temperate and cold temperate climate was respectively assumed to be 50%, 29% and 21% of total area reservoirs and the final numbers are shown in Table 4.1. Emission in tonnes/yr was calculated by multiplying the emission in $gCO_2eqv/m^2/yr$ by respective areas.

Table 4.1 Important parameters to calculate gross emission

	A/V	average soil C	Area (m2)
Total	0,085	4,94	4824370000
0-400	0,167	4,71	1996860000
400-800	0,061	6,47	1635010000
800-1200	0,065	3,35	1083330000
1200+	0,068	3,35	109170000
Warm temperate	0,150	4,95	1399067300
Polar climate	0,090	3,6	2412185000
Cold temperate	0,156	8,628	1013117700

Table 4.2 Gross emission in Norway

CO2eqv		Global mean horizontal radiance (Case 2)		Summer horizontal radiance (Case 1)		Difference (Case1-Case2)
Categories		g/m2/yr	tonnes/yr	g/m2/yr	tonnes/year	tonnes/yr
0-400	CH4	38,4	76608,8	69,3	138420,5	61811,7
	CO2	63,6	126974,7	63,6	126974,7	0
400-800	CH4	20,9	34200,7	29,1	47543,0	13342,3
	CO2	82,2	134465,1	82,5	134817,9	352,7
800-1200	CH4	23,9	25845,3	27,2	29466,3	3621,0
	CO2	49,2	53299,8	49,2	53299,8	0
1200-200	CH4	7,9	858,5	8,9	967,6	109,2
	CO2	46,0	5021,8	46,0	5021,8	0
Sum of results from Altitude range					536511,6	
Warm temperate	CH4	48,7	68154,5	93,3	130513,6	62359,0
	CO2	65,6	91740,1	65,6	91740,1	0
Polar Climate	CH4	22,7	54697,3	27,5	66312,1	11614,8
	CO2	52,5	126640,9	52,5	126640,9	0
Cold Temperate	CH4	26,5	26864,0	25,6	25936,1	-927,9
	CO2	104,5	105909,4	104,6	105974,2	64,8
Sum of results from Climate zone					547116,9	
Total	CH4	23,9	115093,0	33,3	160675,8	45582,8
	CO2	66,0	318408,4	66,0	318408,4	0

The variable Area/Volume (A/V) at HRV is was found most significant for the calculation of methane, and for the calculation of carbon dioxide, soil carbon content was found to have high significance from the results generated from the inputs of studied reservoirs across Norway (UNESCO/IHA, 2018). Incase, of the categories with respect to the altitude the A/V ratio was calculated from the ratio of total area to the total volume of each altitude range in Norway and the soil carbon content was the average of the studied sites in each altitude range.

Similarly, for climate zones both the A/V ratio and soil carbon content was assumed to be the average value of the A/V ratio and soil carbon in respective climate zones from the reservoirs understudy as shown in Table 4.1. The minimum, average and maximum values for soil carbon was assumed like the assumption of soil carbon but the A/V ratio was assumed to be the same.

In Table 4.2 the sum of results from the altitude range and sum of results from climate zone is almost the same but since all the parameters in the climate zone is assumed the result from the altitude range is more accurate and is $536*10^3$ tonnesCO_2eqv/yr and the emission intensity is 3.8 gCO_2eqv/kWh. If the single formulae generated for the whole Norway is used the total emission is $479*10^3$ tonnesCO_2eqv/yr and the emission intensity is 3.4 gCO_2eqv/kWh. The value is low compared to the sum because the low cumulative A/V ratio (0.085) in whole Norway would lower results from the reservoirs in altitude range of 0-400 masl which has higher A/V ratio (0.167) and shares 42 % of total reservoir area in Norway.

Table 4.3 Statistics of gross emissions in Norway

	GHG emission intensity (gCO_2eqv/kWh)
Minimum	2,4
Median	3,8
Mean	3,8
Maximum	6,4

The A/V ratio is the same for all the categories because it is calculated from the standard values but the values of soil carbon content can change. If we input the maximum, minimum and median soil carbon content from the studied reservoirs to our generated formulae the GHG emission intensity can go as high as 6.4 gCO_2eqv/kWh and as low as 2.4 gCO_2eqv/kWh, the median value would be the same as the average. The input of impounded soil carbon is not reliable because the soil carbon values for only the limited reservoirs are only studied.

4.3 Cumulative effect of climate zones and altitude range

A table of formulae sheet was developed for the emission to study the combined effect of categorization by altitude and climate zone, so that different altitude range in each of the climate zones could be separately studied. The Table 4.4 shows the formulae for the cumulative effect of climate zones and altitude.

Table 4.4 Formulae for combined effect of climate zones and altitude range

Climate	Altitude	0-400	400-800	800-1200	1200+	Total
Warm Temp	CO2 (R2)	y = 12,097z + 7,7419(1)	y = 10,327z + 12,404 (1)	47,5	–	y = 10,434z + 13,924 (0,9884)
	CH4 (R2)	y=203,4x+114,01 (0,1478)	y = 875,58x - 8,5947 (1)	y = 77,845x + 37,262 (1)	–	y = 517,84x + 15,384 (0,6064)
Polar climate	CO2 (R2)	y = 12,485z + 8,5001 (0,9777)	y = 11,514z + 11,431 (0,9989)	50,3	46	y = 11,773z + 9,7743 (0,9723)
	CH4 (R2)	y = 454,75x - 22,976 (0,8258)	y = 154,32x + 18,845 (0,3938)	y = 255,71x + 7,834 (0,9987)	y = 142,96x - 0,8144 (1)	y = 257,16x + 4,3252 (0,5735)
Cold Temp	CO2 (R2)	y = 10,442z + 14,383 (0,9996)	y = 7,7419z + 47,097 (1)	–	–	y = 10,352z + 15,285(0,9977)
	CH4 (R2)	y = 54,298x + 14,658 (0,4126)	y = 167,31x + 6,7636 (1)	–	–	y = 61,461x + 15,982 (0,3866)
Total	CO2 (R2)	y = 10,541z + 14,108 (0,9949)	y = 10,318z + 15,372 (0,9933)	49,2	46	y = 10,495z + 13,894 (0,9932)
	CH4 (R2)	y = 356,91x + 10,141 (0,2154)	y = 117,93x + 20,979 (0,1986)	y = 259,01x + 10,37 (0,844)	y = 142,96x - 0,8144 (1)	y = 351,8x + 3,5334 (0,3778)

In Table 4.4,

x= maximum area to volume ratio (km^2/million m^3) of reservoirs in the respective zones

y= GHG emission (g CO_2eqv/m^2/year)

z= total impounded soil carbon content (kg C/m^2)

The parameters in each of the categories (for example warm temperate zone with altitude range from 0-400 masl, etc.) is unavailable and so it is not feasible to find the emission in each of the categories. A detailed study of the soil carbon content under impoundment, area of reservoirs in individual regions and area-volume ratio of the reservoirs in each region should be carried out before calculating the numerical values of emission in each category, the total emission, and hence the GHG emission intensity. The relationships in Table 4.4 can be a basis for analysis in the future studies.

5 Net GHG emissions from the global reservoirs with field measurements

In this chapter, the net emissions from two reservoirs of Norway, one reservoir of Laos and one reservoir of Albania are calculated from the G-Res tool as mentioned in the Objectives. These results generated from G-Res tool are compared with the field measurement values from SINTEF Energi AS.

5.1 Introduction to reservoirs with field measurement data

The Table 5.1 shows some peculiar features of the reservoirs under study i.e. Follsjø, Svartevatn, Banja and Nam Gnouang respectively.

Table 5.1 Peculiar features of selected reservoirs

Reservoirs	Location	Catchment area (km2)	Reservoir area (km2)	Volume(km3)	Energy (Gwh/yr)
Follsjø	Norway	554	6,75	0,179	805
Svartevatn	Norway	202,2	31,4	1,4	2923
Banje	Albania	2890	14	0,178	255
Nam Gnouang	Laos	2942	105	2,45	294

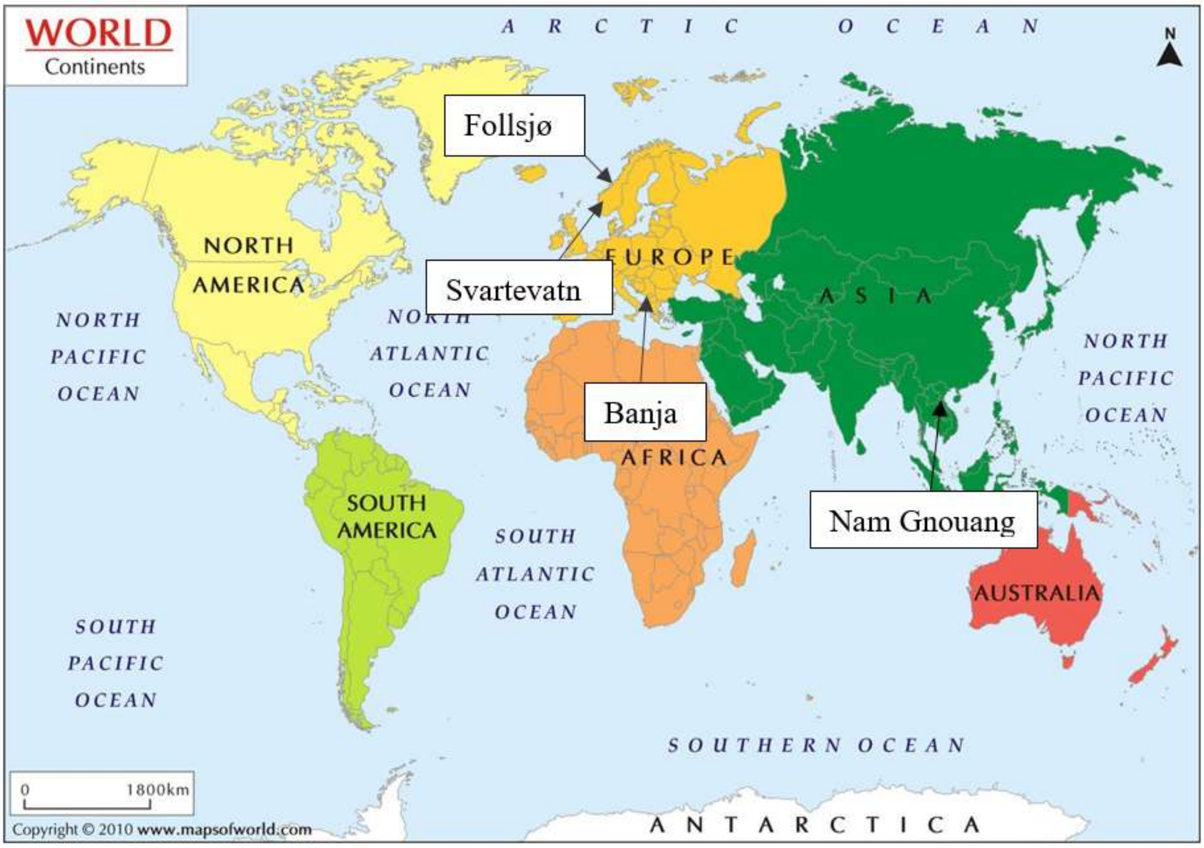


Figure 5.1 Location of the reservoirs with field measurements (mapsofworld, 2010)

Svartevatn reservoir lies in Rogaland and West Agder counties of Norway, produces 2923 Gwh energy annually and has reservoir area of 31.4 km^2. Banja reservoir lies in Elbasan county of Albania, produces 255 Gwh energy annually and has the reservoir area of 14 km^2. Finally, the Nam Gnouang reservoir lies in Bolikhamxay and Khammouane provinces of Laos, produces 294 Gwh energy annually and has the reservoir area of 105 km^2 as shown in the Table 5.1. (Statkraft, 2018) (Sioudom, 2013) (ICEM, 2011) (NVE, 2018) The detailed information to the reservoirs can be found in the Appendix.

5.2 Results from field measurements

The field measurement was carried out in floating chambers which collect the gases in a chamber of known volume and surface area connected to gas analyzer via tubing.

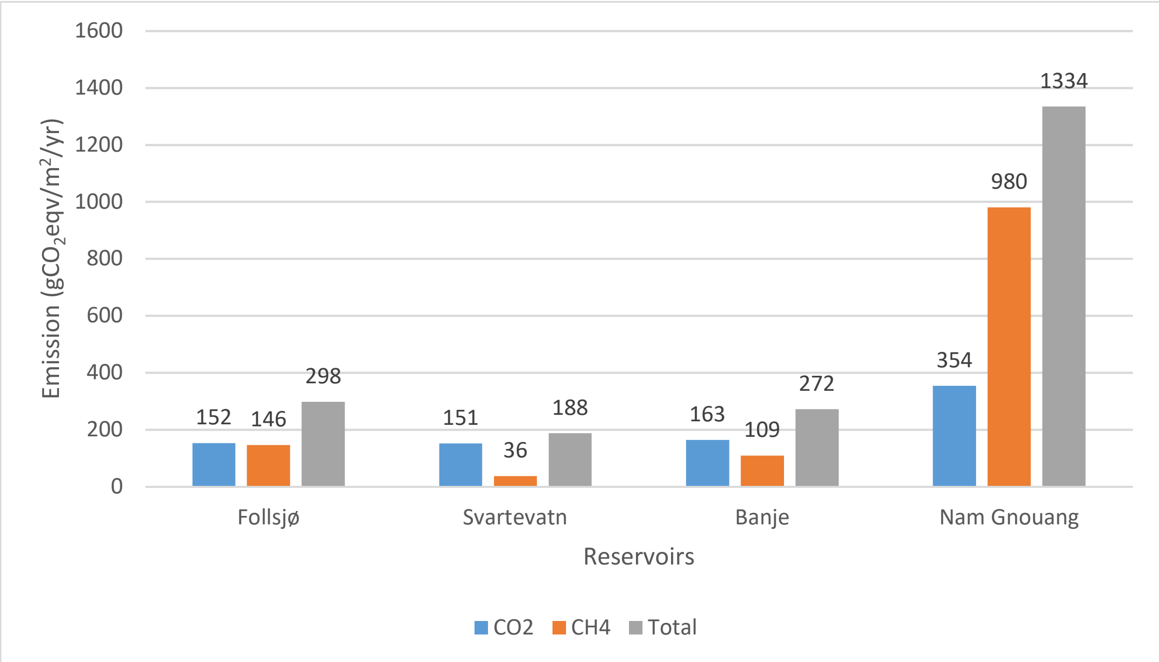


Figure 5.2 Net GHG emission data from field measurement

The Figure 5.2 shows the on-field measurement results of net GHG emission measurement results in Follsjø, Svartevatn, Banja and Nam Gnouang reservoirs. The emission from Svartevatn is low compared to other regions because it lies in the high altitude (LRV= 780 masl) and polar climate region of Norway and there is low temperature and very low vegetation. In Follsjø the emission is comparatively higher than the svartevatn because it lies in the lower altitude (LRV= 375 masl) and cold temperate climate region of Norway and hence there is more temperature and soil carbon content as discussed in 2.3.2.

The emission from Banja is comparatively not so much higher than the emission from the two Norwegian reservoirs even if the reservoir in in the Mediterranean region. The main reason behind this is probably the measurement of emission in the Norwegian reservoirs right after the ice breakage. When the measurement is taken right after the ice-breakage all the trapped gases will be released and will be recorded in the measuring chambers (Harby, Guerin, Bastien, & Demarty, 2012) which can influence higher average emissions. Hence, the emission in Norway could have been overestimated. Similarly, Nam Gnouang reservoir lies in the tropical climate region with a lot of vegetation before the impounded and it is sensible to have higher emission in the reservoirs with such characteristics.

5.3 Results from the G-Res tool

The Figure 5.3 shows the emission results from the G-Res tool and results were generated as described in 3.2.

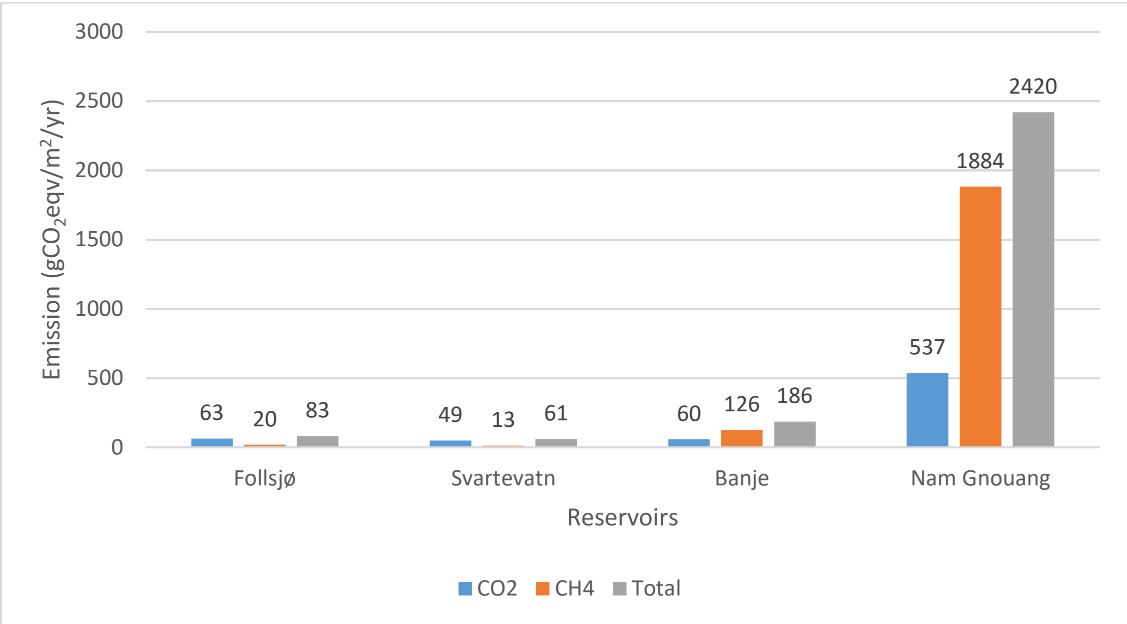
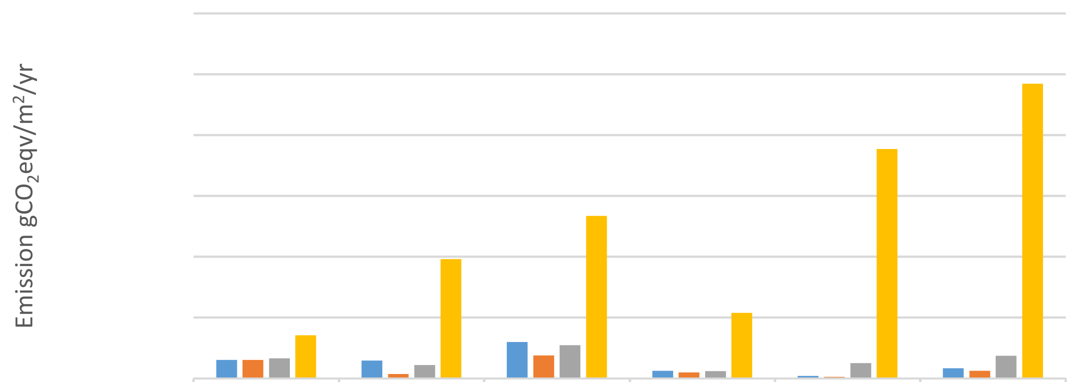


Figure 5.3 Net GHG emission results from the G-Res tool

In each of the reservoirs there was no UAS and it is the net emission without considering the construction of the dam. Svartevatn has the least emission of 61 $gCO_2eqv/m^2/yr$, which is definitely due to its location in high altitude and low impounded soil carbon content. Follsjø has emission of 83 $gCO_2eqv/m^2/yr$, which is higher than Svartevatn because it lies in lower altitude than Svartevatn. Banja reservoir lies in Mediterranean region and so has higher emission than the two Norwegian reservoirs, which is 186 Emission $gCO_2eqv/m^2/yr$. Finally, Nam Gnouang has very high emissions compared to the three other reservoirs because it lies in tropical region and the reservoir impounded area had 53.6 % croplands, 21.1 % forest and 1.5 % settlements. (ICEM, 2011) It is obvious to have high emission in the region with such pre-impoundment conditions.

5.4 Comparison of the results from G-Res tool and field measurements

The Figure 5.4 shows the results for the comparison of G-Res and field measurement values of net GHG emission. The results from the G-Res tool seems to be underestimated compared to the field measurement values. It is actually not underestimated because the emission results from the G-Res tool is the average annual emissions from the reservoir within the life of the reservoir (100 years). The field measurement result is however a recent value. For example, Banja was impounded in 2016 and the field measurement was carried out in February and August of 2017 and emission more than the G-Res result is highly likely because of the emission measurement not even a year after impoundment.



	Field measurement			G-Res result		
	CO2	CH4	Total	CO2	CH4	Total
Follsjø	152	146	298	63	20	83
Svartevatn	151	36	188	49	13	61
Banje	163	109	272	60	126	186
Nam Gnouang	354	980	1334	537	1884	2420

Figure 5.4 Comparison of net GHG emission

Further, the field measurement of the reservoir emission is not carried out all year long or for some years. The measurement is carried out only during a certain period of time and is considered to be the same all year long, which in reality is not the case because the emission would depend on the time of the day and also the season of the year (temperature and sunlight plays an important role). The site of data sampling also plays an important role in the emission data because some regions within the same reservoir may have higher emissions compared to others depending on shallowness and depth of the measurement site. For example, in Svartevatn the carbon dioxide emission in location 1 for spring was 346.5 $mgCO_2eqv/m^2/day$ and 500.4 $mgCO_2eqv/m^2/day$ in location 2.

Similarly, the methane flux in Banja reservoir during the day of wet season was measured 17.34 $mgCO_2eqv/m^2/day$ and 13.94 $mgCO_2eqv/m^2/day$ during the night of the same season. In the dry season, however the methane flux during the day was 1611.94 $mgCO_2eqv/m^2/day$ and 744.94 $mgCO_2eqv/m^2/day$ during the night in the same season. Even though the field measurement data in not very reliable unless carried out continuously for a long period, it however provides an insight on the extent of emission.

6 Discussions, Conclusions & Recommendations

Several parameters govern the emission of greenhouse gases from a reservoir. A set of formulae was developed for the emission in Norway and the average GHG emission intensity in Norway is approximated to be 3.8 CO_2eqv/KWh. It is however difficult to find a general formula, which can define the emissions from several reservoirs separately. If a certain region has similar climatic conditions in terms of wind speed, temperature, soil cover of a catchment area, soil cover of a reservoir before impoundment, global mean horizontal radiance and soil carbon composition. The total emission from all the reservoirs can be calculated by finding the value of emissions from the representative reservoirs and multiplying it by the total area of the reservoir in that area. It is however highly unlikely such similarities exists between two reservoirs.

It is important to find out the detailed information about the categories described in cumulative effect of climate zones and altitude and the variables that significantly influences emission (A/V and soil carbon content was taken as most significant).

According to (de Wit, Austnes, Hylen, & Dalsgaard, 2015) the average soil carbon under the reservoirs in Norway is 17.8 Kg C/m^2, which seems to be very high for Norway. Therefore, the soil carbon impoundment values from google earth engine facility via G-Res tool was used in this study which uses harmonized world soil database as a source. (UNESCO/IHA, 2018) This method generates the soil carbon in the area. It is likely that the impounded soil carbon values used are not representative of the reservoirs, so a detailed study on the soil carbon under the impoundment area is recommended for further studies. Methods such as buffer method has been developed which approximates the land use in the area near the reservoir, but it is not very easy to approximate the pre-impoundment land usage from it because the soil conditions can quickly change from one nearby place to another, the buffer method is nevertheless a good approximation tool for the already impounded reservoirs. The buffer method was not used in this study because of the time constraints of the project and it would not be enough time to focus on the primary objectives of the project. Finding the impounded soil carbon by buffer method can be a part of another project. In the future, however it is possible to map the land use of the reservoirs before the impoundment and it should be mapped to get a clear idea of soil carbon impoundment and the resulting emissions. In addition, it is important to check if a hydropower reservoir emission per unit energy production has lesser emission per unit energy production of a fossil-fueled source before starting any new project.

Similarly, several variables such as wind velocity, temperature, etc. were retrieved from the stations as near as possible from the reservoirs, but it would be more appropriate to find the temperature and wind velocity from site of study. So it is recommended to find the measured values of variables in selected sites of study.

The on-field emission data was measured at some specific days only and it might not be the appropriate values for all the year. The emission can fluctuate due to various parameters depending on what time of the day or year the measurements were taken, if the measurements were done in the shallow or deep side of the reservoir, as discussed in chapter 5. It is recommended to make frequent emission measurements in different sites to find the true pattern of emission.

To solve the problem with high records in emission measurements after the spring ice-breakage a correction factor should be assigned for the emission after the ice-breakage. It is thus recommended to develop a correction factor to be used in emission results after the ice-breakage.

In the G-Res tool the results provide information about only the GHG average annual emission for the life time of the reservoir (100 years). It will be very convenient if G-Res tool develops a representative curve for emission every year after the inundation for the lifetime of the project. It is therefore recommended that the G-Res tool develops an emission curve for the lifetime of the reservoir along with the present information of average annual GHG emission.

This report comes up with many important numerical results and some formulae that can be quantified if the missing variables are determined by further studies. There is a huge gap of information in the study of greenhouse gas emission from freshwater reservoirs. It is however important to continue in the footsteps of the previous research and go even further to see a clear picture through many industrial research activities. Moreover, there is no denying that depending upon the location and characteristics of hydropower reservoir a notable amount of greenhouse gas emissions occurs. So, if the stakeholders of the hydropower production want to live up with competitiveness of the energy industry with respect to GHG emission intensity per KWh against other sources of energy, it is high time they invest on quantifying the various factors which govern emission and hence total emission intensity. Thus, investments in the field of relevant industrial research is a must for competitiveness of the hydropower industry in the future.

References

Barros, N., Jonathan J., C., Lars J., T., Yves T., P., Bastviken, D., Vera LM, H., . . . Roland, F. (2011). Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. *Nature Geoscience, 4(9)*, 593.

Bastien, J., Maud, D., & Tremblay, A. (2011). CO2 and CH4 diffusive and degassing emissions from 2003 to 2009 at Eastmain 1 hydroelectric reservoir, Québec, Canada. *Inland waters, 1*, 113-123.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., & Melack, J. (2007). Plumbing the Global Carbon Cycle: Integrating Inland Waters into the Terrestrial Carbon Budget. *Ecosystems, 10(1)*, 172-185.

de Wit, H. A., Austnes, K., Hylen, G., & Dalsgaard, L. (2015). A carbon balance of Norway: terrestrial and aquatic carbon fluxes. *Biogeochemistry, 123(1-2)*, 147-173.

Dean, W. E., & Gorham, E. (1998). Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology, 26(6)*, 535-538.

Deemer, B. R., Harrison, J. A., Li, S., Jake J., B., Tonya, D., Nathan, B., . . . J. Arie, V. (2016). Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis-Supplementray material. *Bioscience oxford Journal*.

Deemer, B. R., John A., H., Li, S., Jake J., B., Tonya, D., Nathan, B., . . . J. Arie, V. (2016). Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis. *Bioscience Oxford Journal, 66(11)*, 949–964.

Demarty, M., & Bastien, J. (2011). GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH4 emission measurements. *Energy Policy, 39(7)*, 4197-4206.

dos Santos, M. A., Damázio, J. M., Rogério, J. P., Amorim, M. A., Medeiros, A. M., Souza, J. L., . . . Rosa, L. P. (2017). *Estimates of GHG emissions by hydroelectric reservoirs: The Brazilian case.* Elsevier Ltd.

eklima. (2018, 06 07). Retrieved from www.eklima.met.no

Fearnside, P. M. (2008). A Framework for Estimating Greenhouse Gas Emissions from Brazil's Amazonian Hydroelectric Dams. *Oecologia Brasiliensis 12 (01)*, 100-115.

Førsund, F. R. (2013). Hydropower Economics: An Overview. *Encyclopedia of Energy, Natural Resource, and Environmental Economics*.

Goldenfum, J. A. (2010). *GHG Measurement Guidelines for Freshwater Reservoirs: Derived From: The UNESCO/IHA Greenhouse Gas Emissions from Freshwater Reservoirs Research Project.* London: International Hydropower Association (IHA).

Harby, A., Guerin, F., Bastien, J., & Demarty, M. (2012). *Greenhouse gas status of hydro reservoirs.* Center for Environmental Design of Renewable Energy (CEDREN).

Hulme, M., Barrow, E. M., Arnell, N. W., Harrison, P. A., Timothy C., J., & and Thomas E., D. (1999). Relative impacts of human-induced climate change and natural climate variability. *Nature 397, (6721)*, 688.

Hällqvist, E. (2012). *Methane emission from three tropical hydroelectrical reservoir.* Committee of Tropical Ecology, Uppsala University, Uppsala, 46.

ICEM. (2011). *Theun Hinboun Expansion Project – Review of ESIA. Prepared for MK1, Mekong Challenge Program on Water & Food.* Hanoi: ICEM.

IHA. (2018, 05 05). Retrieved from https://www.hydropower.org/news/g-res-new-tool-for-measuring-carbon-footprint-of-reservoirs

IPCC. (2012). *Special Report on Renewable Energy Sources and Climate Change Mitigation.* IPCC.

Juutinen, S., Alm, J., Martikainen, P., & Silvola, J. (2001). Effects of spring flood and water level draw-down on methane dynamics in the littoral zone of boreal lakes. *Freshwater Biology, 46(7)*, 855-869.

Kumar, A., & Sharma, M. P. (2016). Green House Gas emissions from Hydropower Reservoirs: Policy and Challenges. *International Journal of Renewable Energy Research (IJRER) , 6(2)*, 472-476.

latitudelongitude.org. (2018, 06 05). Retrieved from http://latitudelongitude.org/no/kristiansand/

mapsofworld. (2010). Retrieved from www.mapsofworld.com.

Met.no. (2018).

NASA. (2018). *NASA earth observatory*. Retrieved from https://earthobservatory.nasa.gov/Features/EnergyBalance/page6.php

NVE. (2018). Retrieved from nve.no

NVE. (2018). *NEVINA*. Retrieved from www.nevina.nve.no

NVE. (2018). *NVEatlas*. Retrieved from www.atlas.nve.no

Prairie, Y. T., Alm, J., Harby, A., Mercier-Blais, S., & Nahas, R. (2017). *The GHG Reservoir Tool (G-res) User guide, UNESCO/IHA research project on the GHG status of freshwater reservoirs.Version 1.1. Joint publication of the UNESCO Chair in Global Environmental Change and the International Hydropower Association. 38 pages.* Retrieved from https://www.hydropower.org/sites/default/files/G-Res%20Tool%20User%20Guide_0.pdf

Prairie, Y., Alm, J., Harby, A., Mercier-Blais, S., & Nahas, R. (2017). *The GHG Reservoir Tool (Gres) Technical documentation, UNESCO/IHA research project on the GHG status of freshwater reservoirs.* UNESCO Chair in Global Environmental Change and the International Hydropower Association.

Raval, A., & Ramanathan, V. (1989). Observational determination of the greenhouse effect. *Nature 342, (6251)* , 758.

Senorge. (2018, 6 5). *Senorge*. Retrieved from http://www.senorge.no/?p=klima&m=bmNVEGrey%3BMapLayer_rryr30yr_19611990%3B&l=no&d=1519290000000&e=-1143879%7C6046683%7C2147967%7C8325237&ft=&fh=0%3B2468

Sioudom, K. (2013). *Basin Profile for the Nam Theun/Nam Kading, Nam Hinboun and Xe Bang Fai, Lao PDR. Project report: Challenge Program on Water & Food Mekong project MK3 "Optimizing the management of a cascade of reservoirs at the catchment level".* Hanoi: ICEM – International Centre for Environmental Management, Hanoi Vietnam.

St. Louis, V. L., Kelly, C. A., Duchemin, É., Rudd, J. W., & Rosenberg, D. M. (2000). Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. *BioScience 50*, 766-775.

Statkraft. (2018). *Statkraft*. Retrieved from https://www.statkraft.com/energy-sources/Power-plants/albania/banja/

Statkraft. (2018, 6 04). *Statkraft*. Retrieved from https://www.statkraft.com/energy-sources/hydropower/

Theun-hinboun power company, Lao . (2018, 03 15). Retrieved from http://www.thpclaos.com/images/stories/pages/technical%20specs/TechSpecsDetails.pdf

Tremblay, A., & eds. (2005). *Greenhouse gas Emissions-Fluxes and Processes: hydroelectric reservoirs and natural environments.* Springer Science & Business Media.

UNESCO/IHA. (2018, 06 05). *The GHG Reservoir Tool (G-Res) Scientific guidelines*. Retrieved from https://www.hydropower.org/sites/default/files/G-res%20Scientific%20Guidelines.pdf

WNA. (2011). *Comparision of lifecycle greenhouse gas emission of various electricity generation sources.* London: World Nuclear Association.

Yang, L., Lu, F., Zhou, X., Wang, X., Duan, X., & Sun, B. (2014). Progress in the studies on the greenhouse gas emissions from reservoirs. *Acta Ecologica Sinica, 34(4)*, 204-212.

Appendices

A. Graphs and equations on gross emission in Norway

		Case 2 (gCO2e/m2/yr)		Case 1 (gCO2e/m2/yr)	
Categories		Equation	R2	Equation	R2
0-400	CH4	y = 178,14x + 8,6055	0,3844	y = 360,24x + 9,1393	0,2529
	CO2	y = 10,57x + 13,779	0,9946	y = 10,57x + 13,779	0,9946
400-800	CH4	y = 116,31x + 13,825	0,4944	y = 104,87x + 22,683	0,153
	CO2	y = 10,283x + 15,733	0,9936	y = 10,229x + 16,298	0,9927
800-1200	CH4	y = 186,47x + 11,741	0,8492	y = 259,01x + 10,37	0,844
	CO2	49,2		49,2	
1200-200	CH4	y = 142,96x - 1,8144	1	y = 142,96x - 0,8144	1
	CO2	46		46	
Warm temperate	CH4	y = 243,32x + 12,11	0,8884	y = 517,84x + 15,384	0,6064
	CO2	y = 10,434x + 13,924	0,9884	y = 10,434x + 13,924	0,9884
Polar Climate	CH4	y = 146,63x + 9,4521	0,4791	y = 257,16x + 4,3252	0,5735
	CO2	y = 11,773x + 9,7743	0,9723	y = 11,773x + 9,7743	0,9723
Cold Temperate	CH4	y = 122,24x + 7,3863	0,4471	y = 61,461x + 15,982	0,3866
	CO2	y = 10,368x + 15,083	0,9977	y = 10,352x + 15,285	0,9971
Total	CH4	y = 174,68x + 9,085	0,5556	y = 351,8x + 3,5334	0,3778
	CO2	y = 10,458x + 14,304	0,9947	y = 10,495x + 13,894	0,9932

Summer Horizontal Radiance as input (Case 1)

a. Minimum emission

CO2eqv		Global mean horizontal radiance (Case 2)		Summer horizontal radiance (Case 1)		Difference (Case1-Case2)
Categories		g/m2/yr	tonnes/yr	g/m2/yr	tonnes/year	tonnes/yr
0-400	CH4	38,4	76608,8	69,3	138420,5	61811,7
	CO2	37,5	74794,0	37,5	74794,0	0
400-800	CH4	20,9	34200,7	29,1	47543,0	13342,3
	CO2	50,2	82046,5	50,6	82674,5	628,0
800-1200	CH4	23,9	25845,3	27,2	29466,3	3621,0
	CO2	49,2	53299,8	49,2	53299,8	0
1200-200	CH4	7,9	858,5	8,9	967,6	109,2
	CO2	46,0	5021,8	46,0	5021,8	0
Sum of results from Altitude range					432187,5	
Warm temperate	CH4	48,7	68154,5	93,3	130513,6	62359,0
	CO2	48,9	68383,5	48,9	68383,5	0
Polar Climate	CH4	22,7	54697,3	27,5	66312,1	11614,8
	CO2	36,1	87190,4	36,1	87190,4	0
Cold Temperate	CH4	12,0	12189,2	18,3	18557,8	6368,6
	CO2	38,3	38809,8	38,5	38978,2	168,3
Sum of results from Climate zone					409935,5	
Total	CH4	23,9	115093,0	33,3	160675,8	45582,8
	CO2	37,7	182023,1	37,7	182023,1	0

	A/V	min soil C	Area (m2)
Total	0,085	2,24	4824370000
0-400	0,167	2,24	1996860000
400-800	0,061	3,35	1635010000
800-1200	0,065	3,35	1083330000
1200+	0,068	3,35	109170000
Warm temperate	0,150	3,35	1399067300
Polar climate	0,090	2,2	2412185000
Cold temperate	0,156	2,24	1013117700

b. Median emission

CO2eqv		Global mean horizontal radiance (Case 2)		Summer horizontal radiance (Case 1)		Difference (Case1-Case2)
Categories		g/m2/yr	tonnes/yr	g/m2/yr	tonnes/year	tonnes/yr
0-400	CH4	38,4	76608,8	69,3	138420,5	61811,7
	CO2	49,2	98222,5	49,2	98222,5	0
400-800	CH4	20,9	34200,7	29,1	47543,0	13342,3
	CO2	91,4	149465,9	91,6	149739,8	274,0
800-1200	CH4	23,9	25845,3	27,2	29466,3	3621,0
	CO2	49,2	53299,8	49,2	53299,8	0
1200-200	CH4	7,9	858,5	8,9	967,6	109,2
	CO2	46,0	5021,8	46,0	5021,8	0
Sum of results from Altitude range					522681,4	
Warm temperate	CH4	48,7	68154,5	93,3	130513,6	62359,0
	CO2	59,0	82543,4	59,0	82543,4	0
Polar Climate	CH4	22,7	54697,3	27,5	66312,1	11614,8
	CO2	49,2	118712,9	49,2	118712,9	0
Cold Temperate	CH4	26,5	26864,0	25,6	25936,1	-927,9
	CO2	123,4	125047,7	123,5	125083,0	35,3
Sum of results from Climate zone					549101,0	
Total	CH4	23,9	115093,0	33,3	160675,8	45582,8
	CO2	49,3	238026,2	49,3	238026,2	0

	A/V	average soil C	Area (m2)
Total	0,085	3,35	4824370000
0-400	0,167	3,35	1996860000
400-800	0,061	7,36	1635010000
800-1200	0,065	3,35	1083330000
1200+	0,068	3,35	109170000
Warm temperate	0,150	4,32	1399067300
Polar climate	0,090	3,4	2412185000
Cold temperate	0,156	10,45	1013117700

c. Maximum Emission

CO2eqv		Global mean horizontal radiance (Case 2)		Summer horizontal radiance (Case 1)		Difference (Case1-Case2)
Categories		g/m2/yr	tonnes/yr	g/m2/yr	tonnes/year	tonnes/yr
0-400	CH4	38,4	76608,8	69,3	138420,5	61811,7
	CO2	157,5	314567,4	157,5	314567,4	0
400-800	CH4	20,9	34200,7	29,1	47543,0	13342,3
	CO2	155,6	254377,8	155,4	254100,8	-277,0
800-1200	CH4	23,9	25845,3	27,2	29466,3	3621,0
	CO2	49,2	53299,8	49,2	53299,8	0
1200-200	CH4	7,9	858,5	8,9	967,6	109,2
	CO2	46,0	5021,8	46,0	5021,8	0
Sum of results from Altitude range					843387,2	
Warm temperate	CH4	48,7	68154,5	93,3	130513,6	62359,0
	CO2	109,5	153197,1	109,5	153197,1	0
Polar Climate	CH4	22,7	54697,3	27,5	66312,1	11614,8
	CO2	78,4	189141,6	78,4	189141,6	0
Cold Temperate	CH4	44,8	45379,3	34,8	35245,4	-10133,9
	CO2	155,6	157610,1	155,6	157595,1	-15,0
Sum of results from Climate zone					732004,8	
Total	CH4	23,9	115093,0	33,3	160675,8	45582,8
	CO2	156,5	755172,1	156,5	755172,1	0

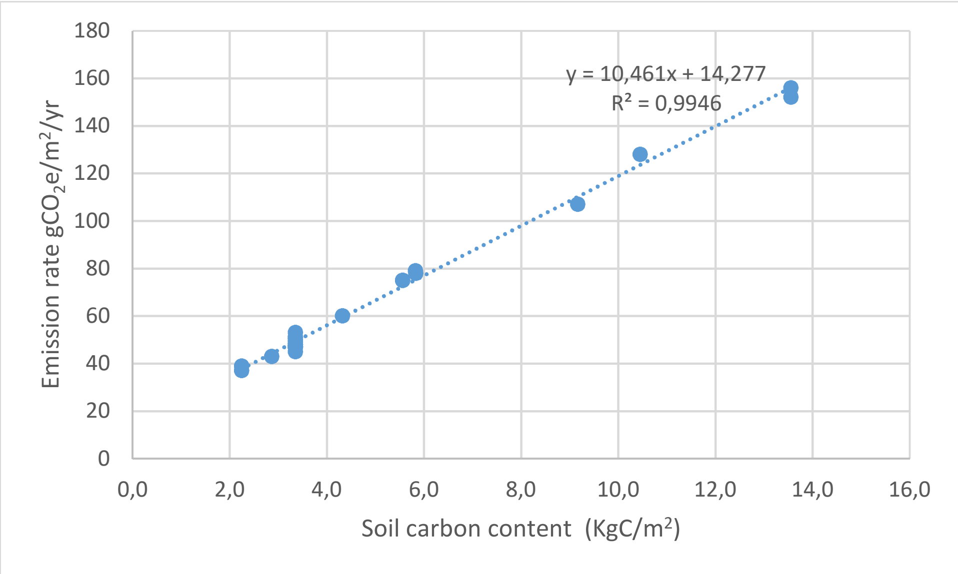
	A/V	Max soil C	Area (m2)
Total	0,085	13,60	4824370000
0-400	0,167	13,60	1996860000
400-800	0,061	13,60	1635010000
800-1200	0,065	3,35	1083330000
1200+	0,068	3,35	109170000
Warm temperate	0,150	9,16	1399067300
Polar climate	0,090	3,6	2412185000
Cold temperate	0,156	13,55	1013117700

Global Mean Horizontal Radiance as input (Case 2)

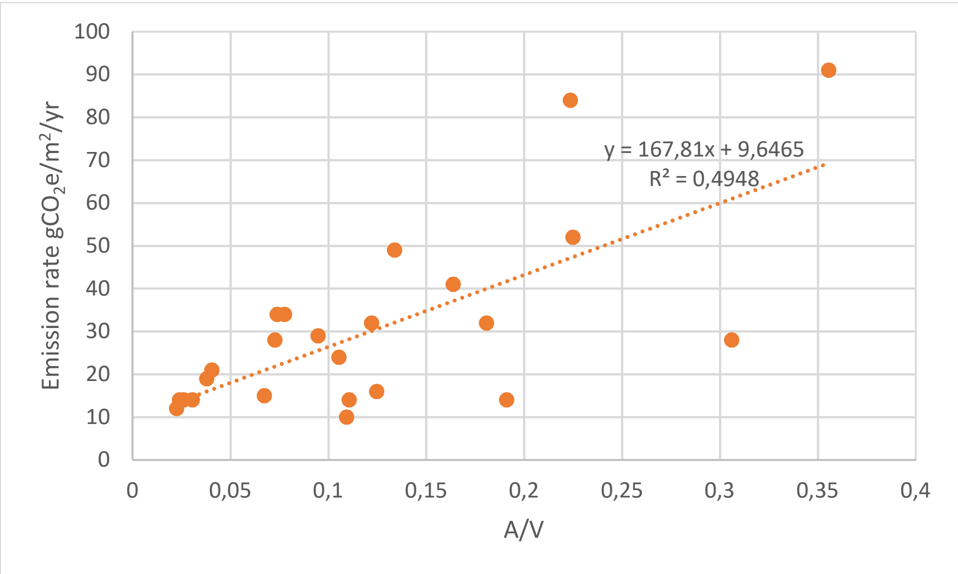
Global mean horizontal radiance is used and the wind velocity is found from nearest available measurement station all other values are chosen as stated in 3.1.2.

Total emission

i. Carbon dioxide



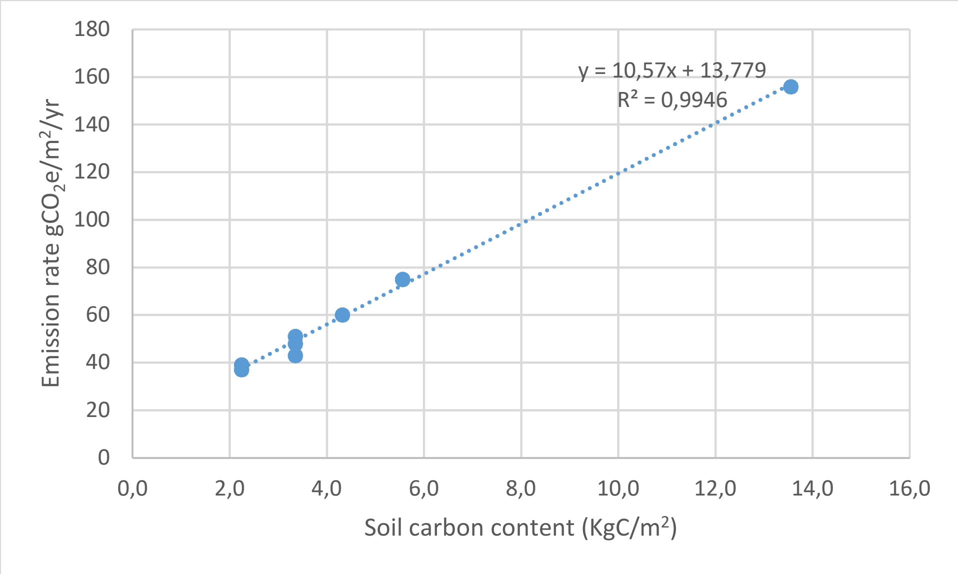
ii. Methane



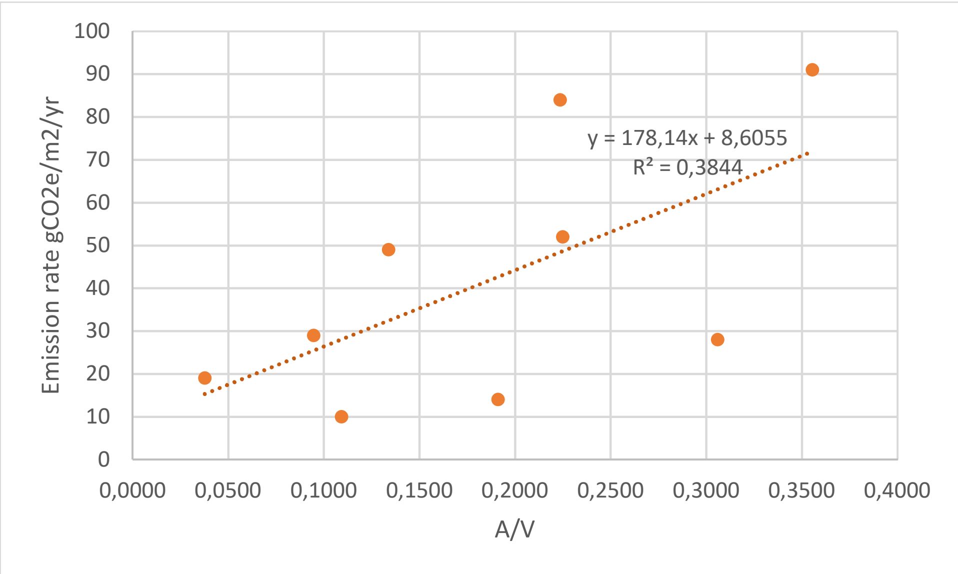
Emission based on altitude

i. 0-400

a) Carbon dioxide

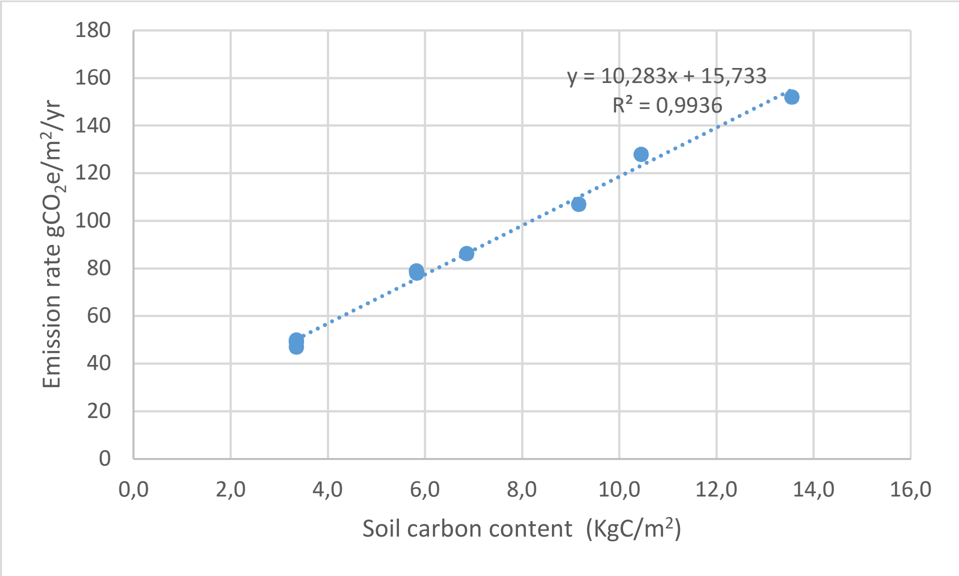


b) Methane

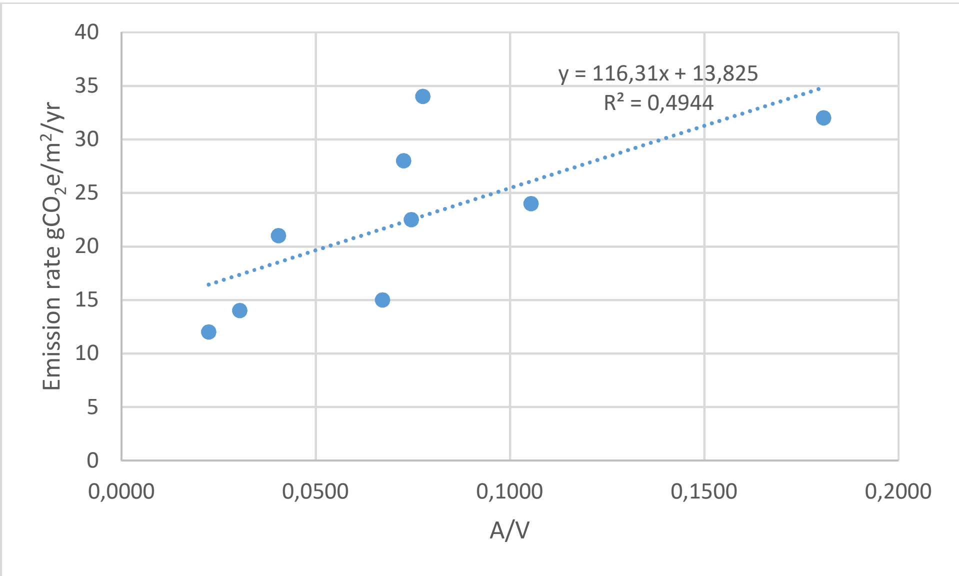


ii. 400-800

a) Carbon dioxide



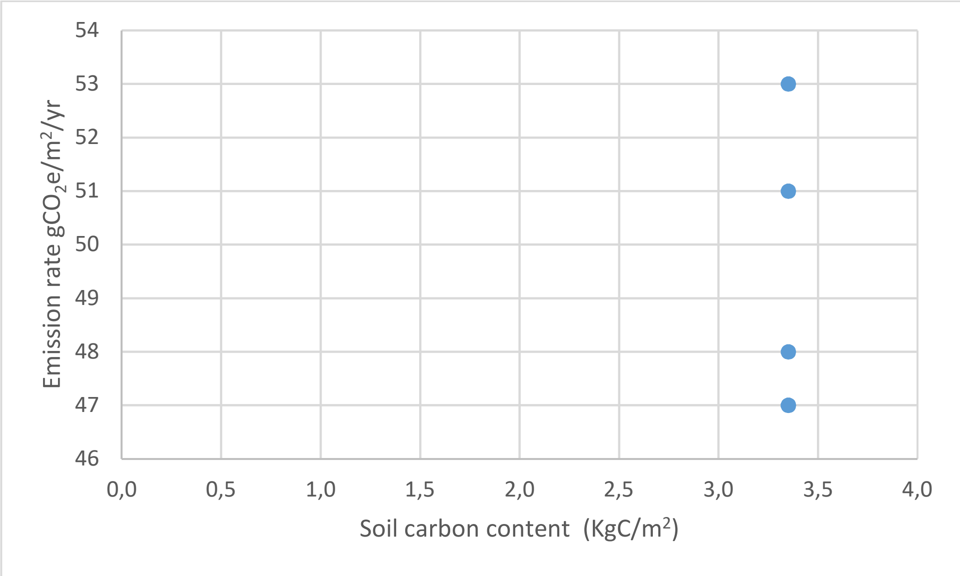
b) Methane



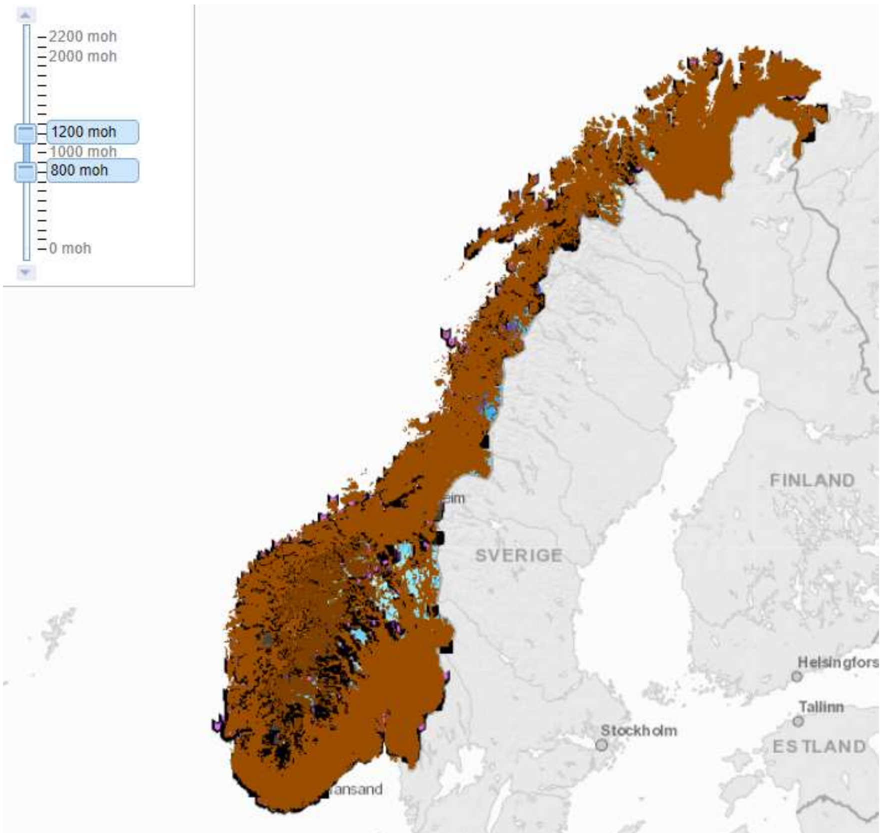
iii. 800-1200

The altitude range and the reservoirs in this range is very limited as seen in the figure below where the altitude outside 800-1200 masl are shaded brown.

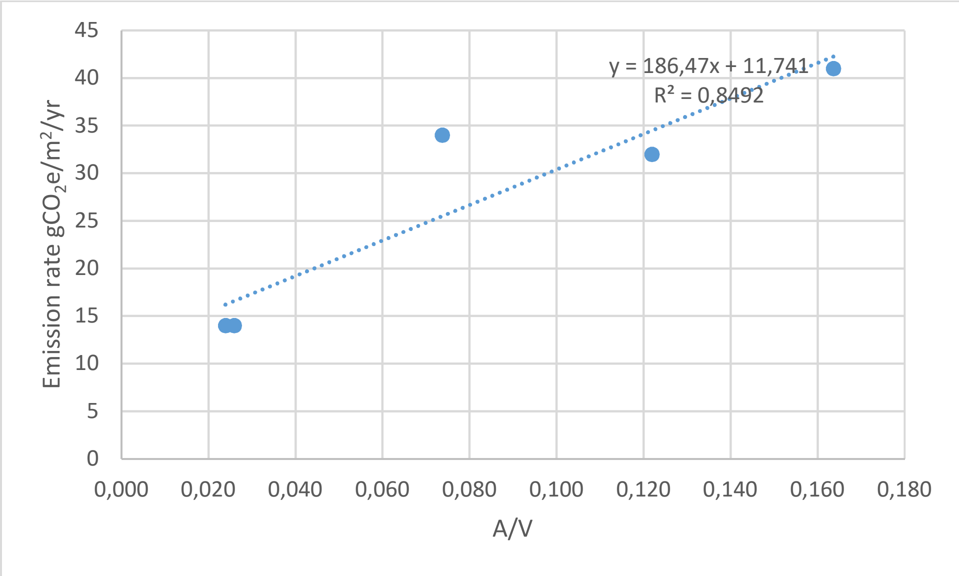
a) Carbon dioxide



Since the reservoirs lie very close to each other the soil carbon content is almost the same and the CO_2 emission rate in the region is assumed average of the results from our selected sites i.e. 49.2 $gCO_2eqv/m^2/yr$.

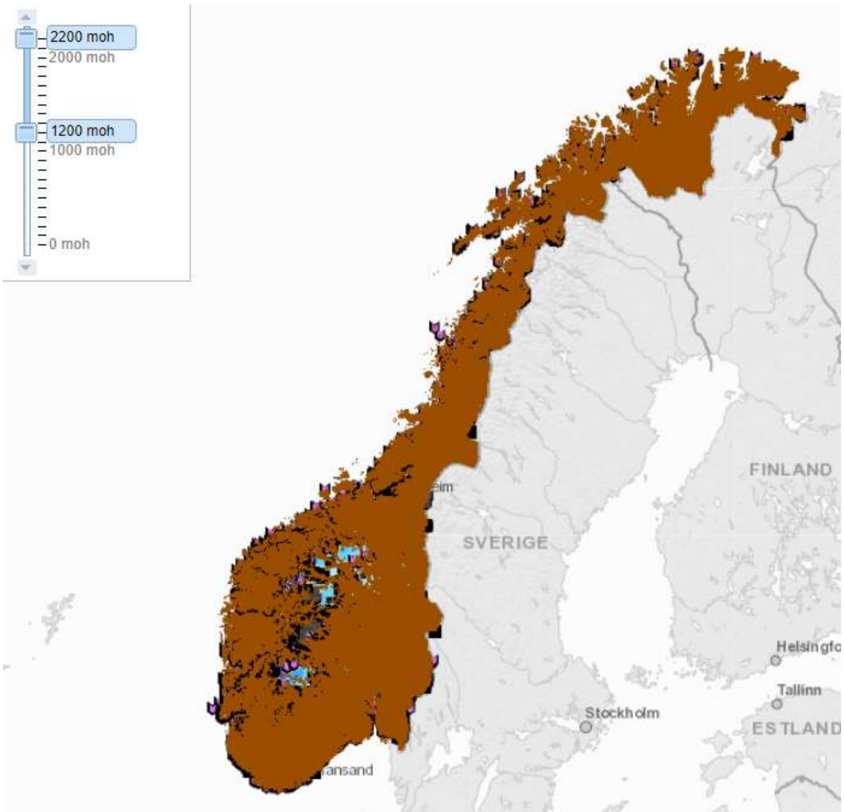


b) Methane



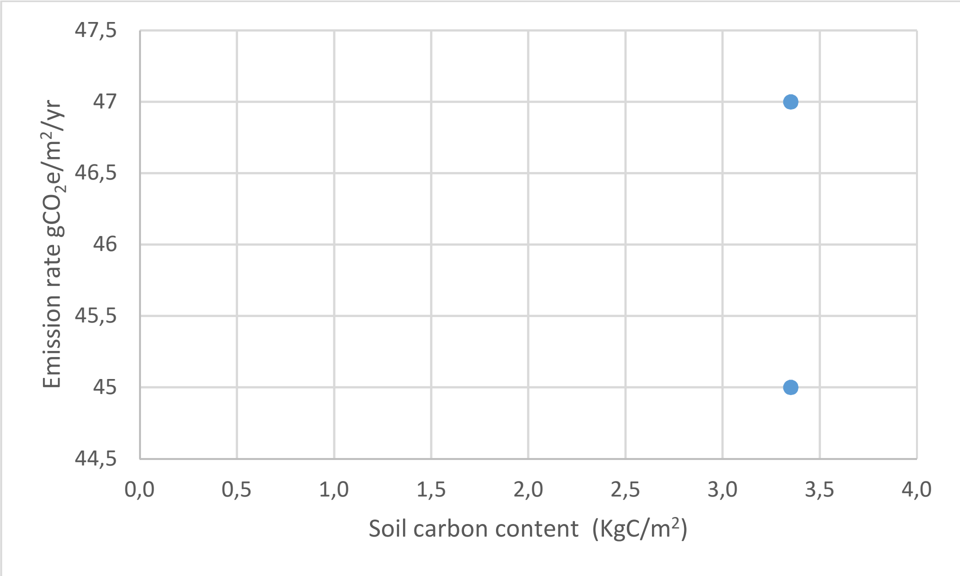
iv. 1200-2200

The altitude range and the reservoirs in this range is also very limited as seen in the figure.. where the altitude outside 1200-2200 masl are shaded brown.



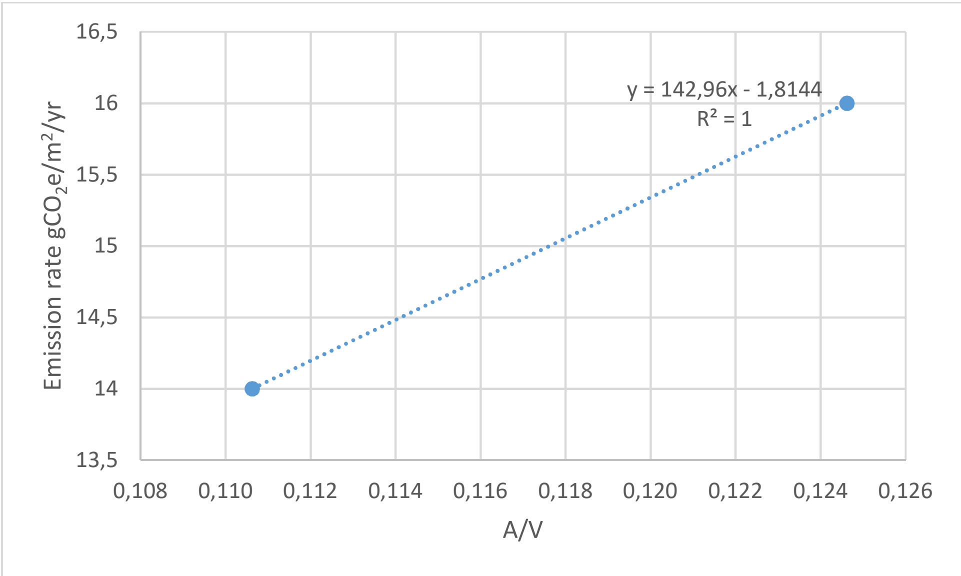
a) Carbon dioxide

The average of the studied sites is taken which is 46 $gCO_2eqv/m^2/yr$.



b) Methane

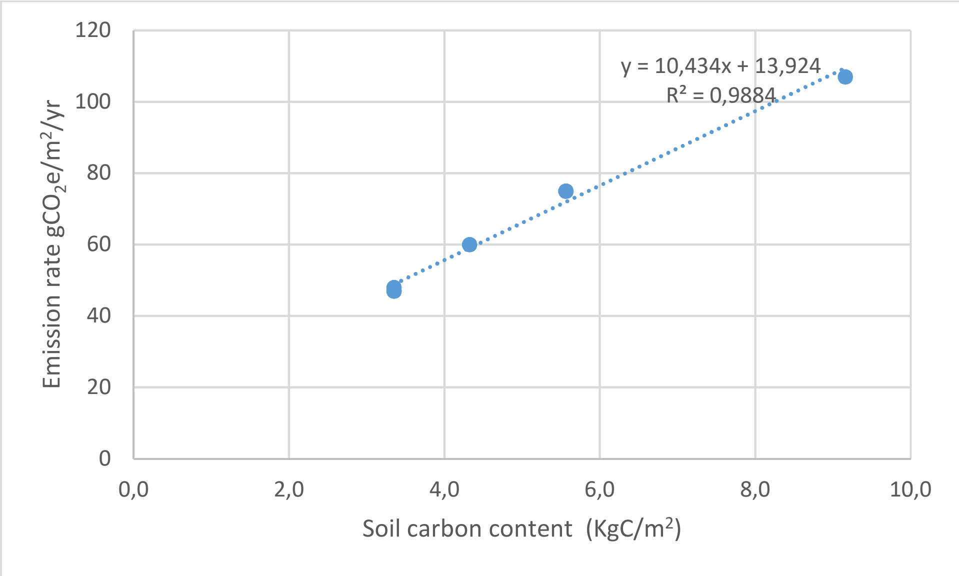
The average of the studied sited is taken which is 15 $gCO_2eqv/m^2/yr$.



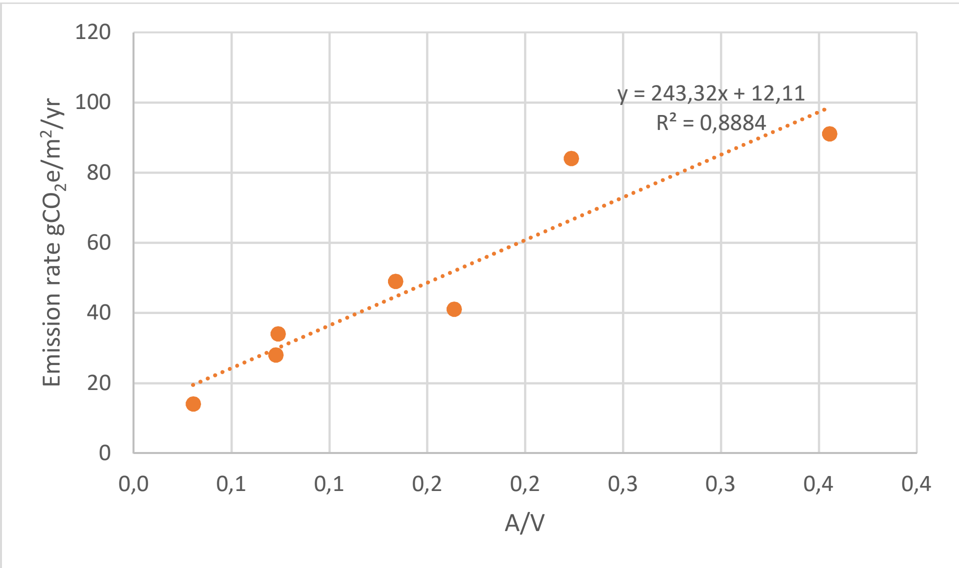
Emission based on Climate zone

i. Warm Temperate:

a) Carbon dioxide

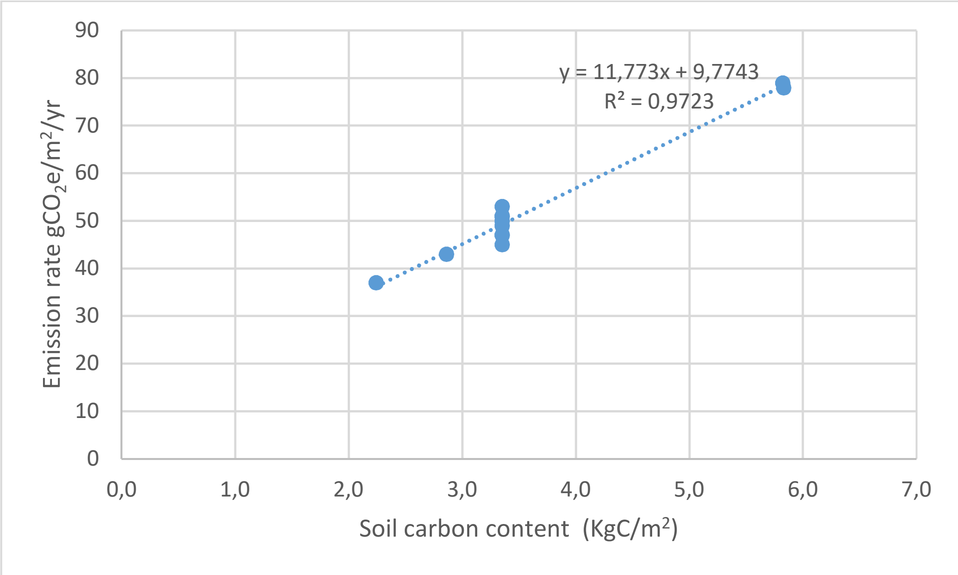


b) Methane

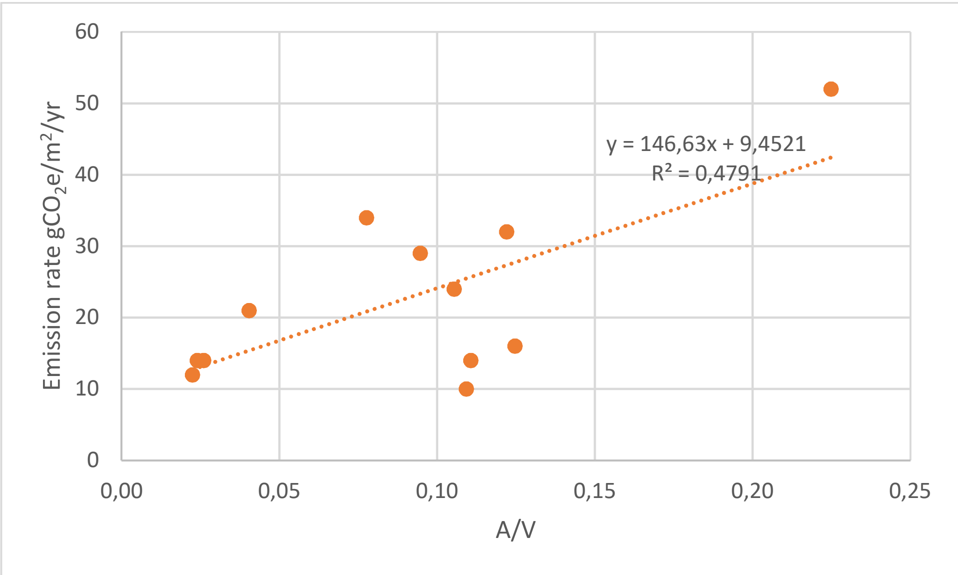


ii. Polar climate:

a) Carbon dioxide

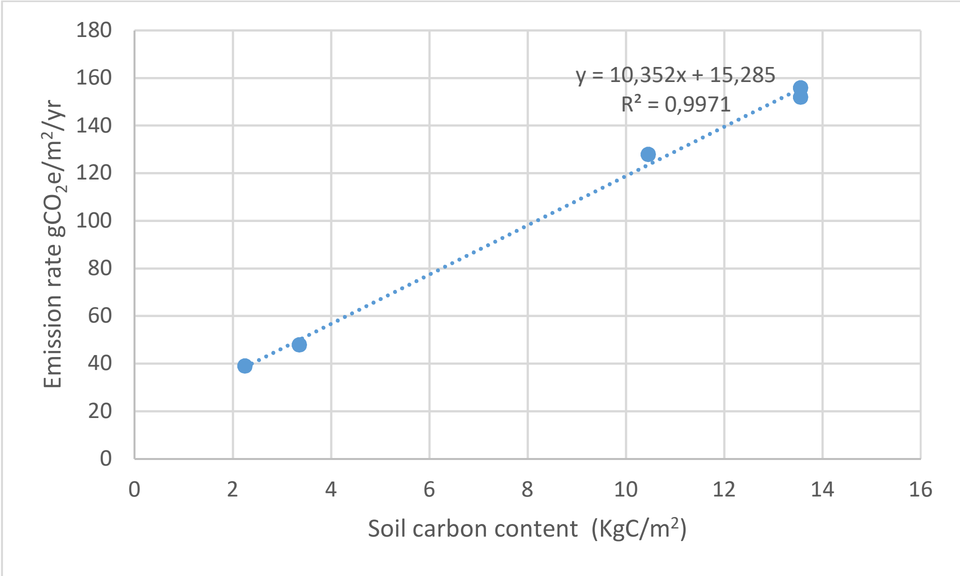


b) Methane



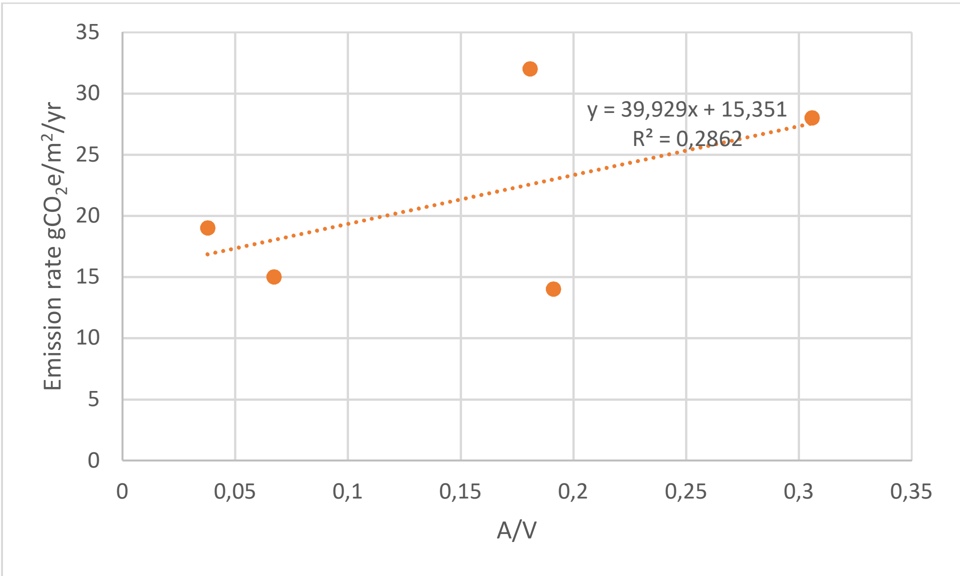
iii. Cold temperate:

a) Carbon dioxide



y = 10,352x + 15,285
R² = 0,9971
Emission rate gCO2e/m2/yr
Soil carbon content (KgC/m2)

b) Methane



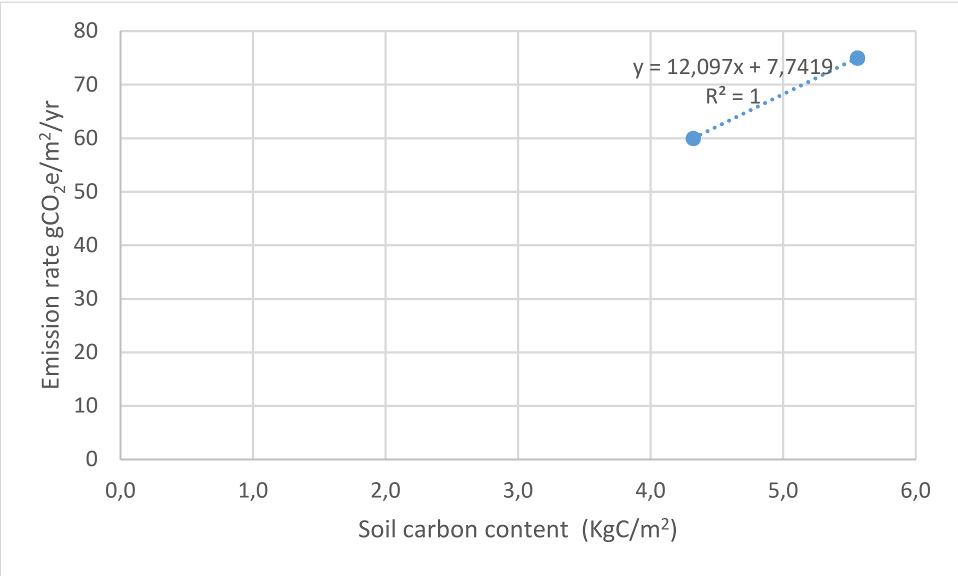
y = 39,929x + 15,351
R² = 0,2862
Emission rate gCO2e/m2/yr
A/V

B. Cumulative effect of Climate and altitude

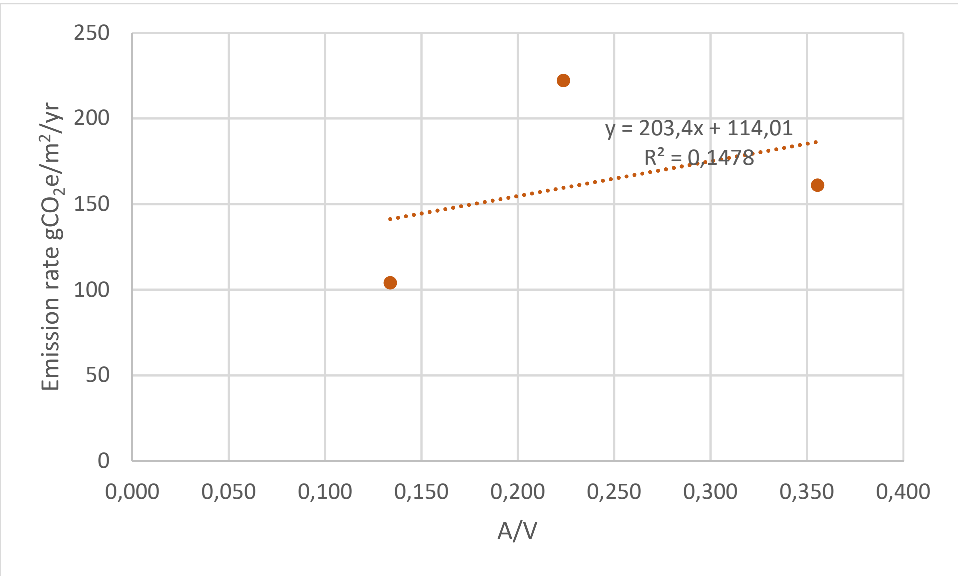
A. Warm Temperate climate zone

i. 0-400 masl

a) Carbon dioxide

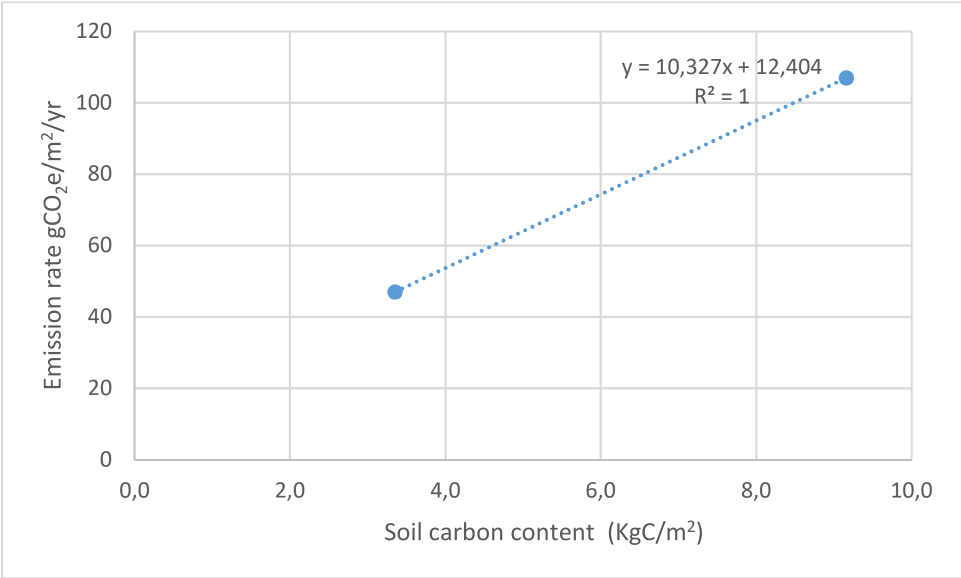


b) Methane

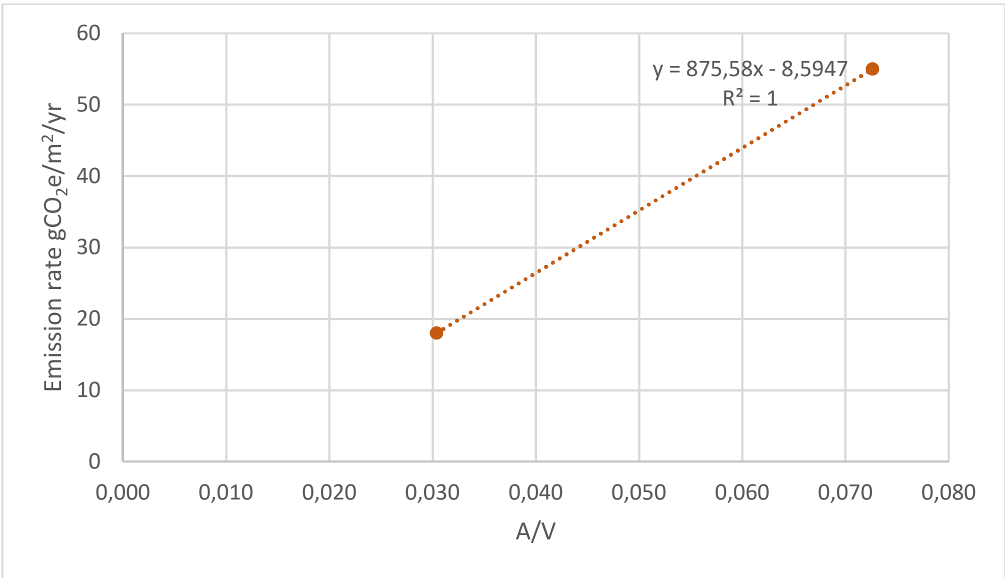


ii. 400-800 masl

a) Carbon dioxide

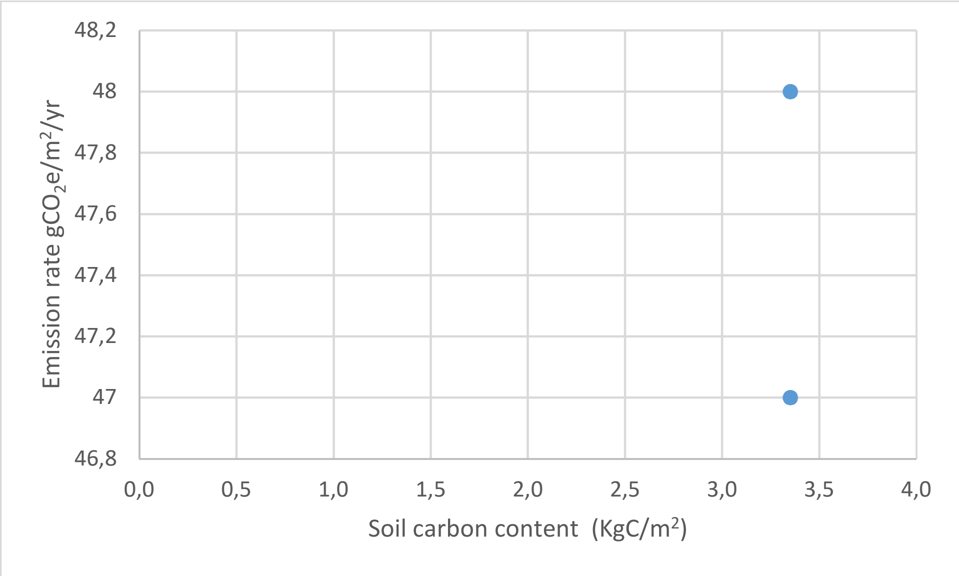


b) Methane

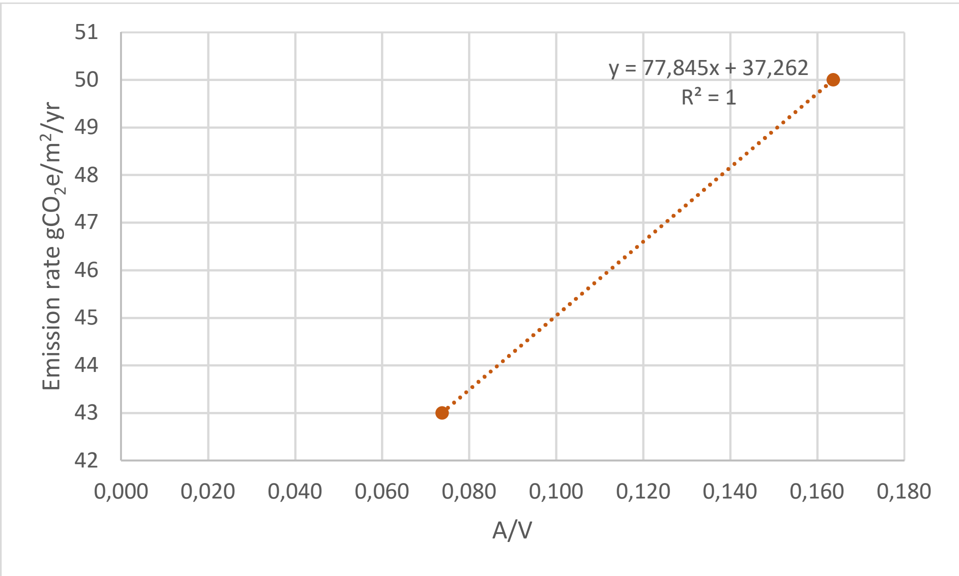


iii. 800-1200 masl

a) Carbon dioxide



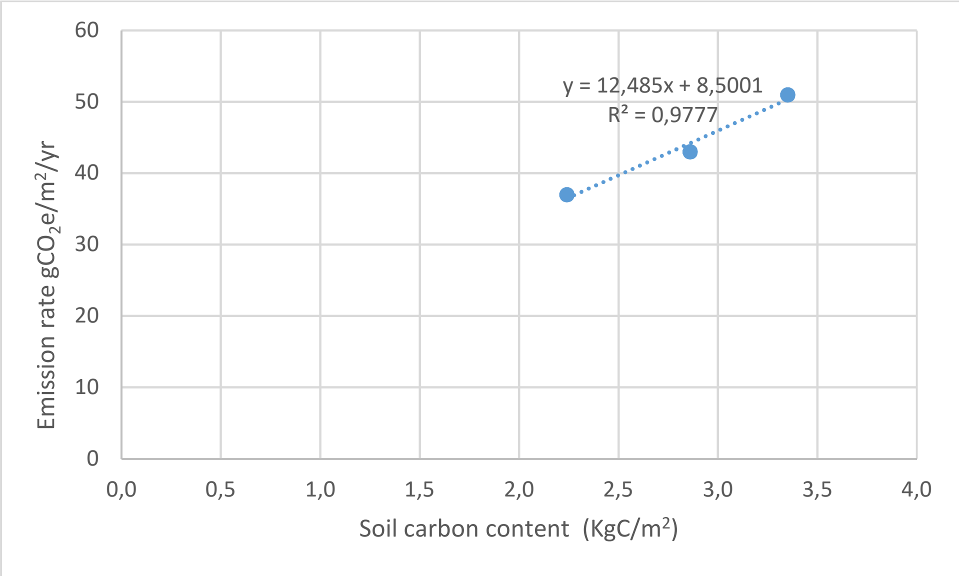
b) Methane



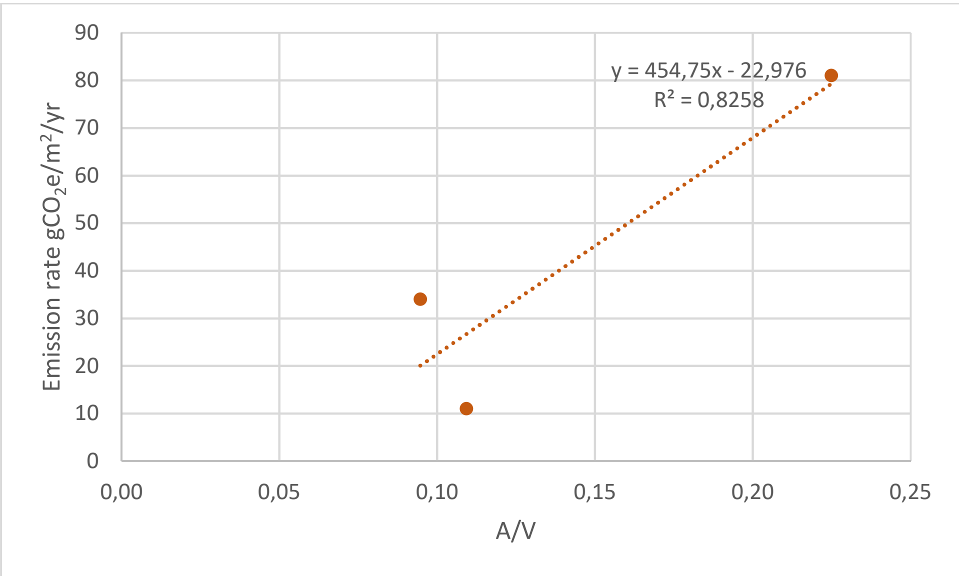
B. Polar climate zone

i. 0-400 masl

a) Carbon dioxide

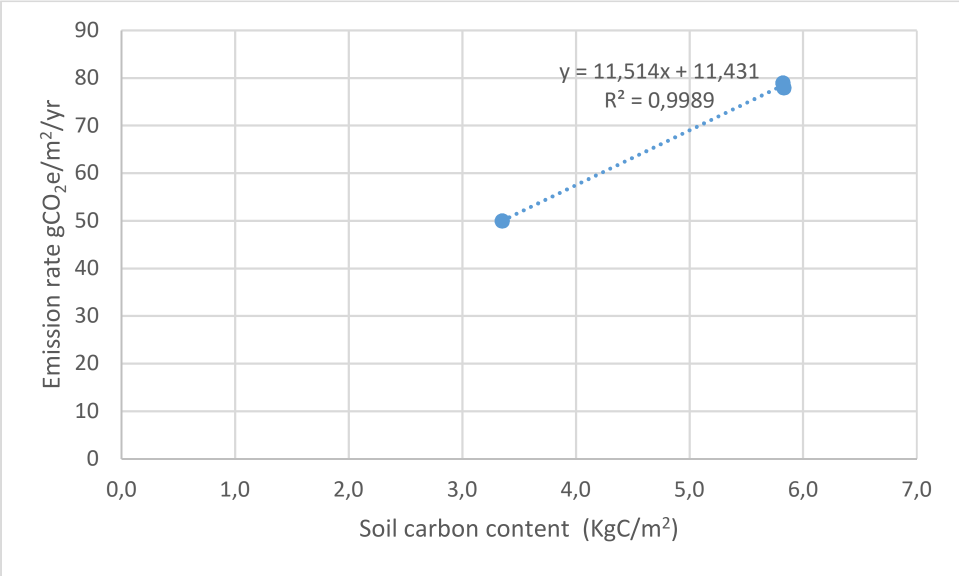


b) Methane

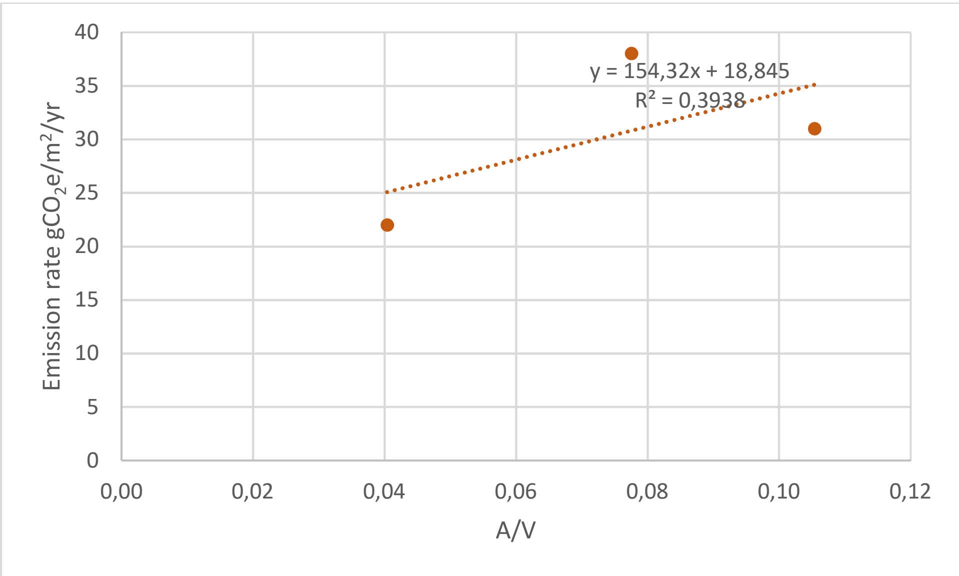


ii. 400-800 masl

a) Carbon dioxide

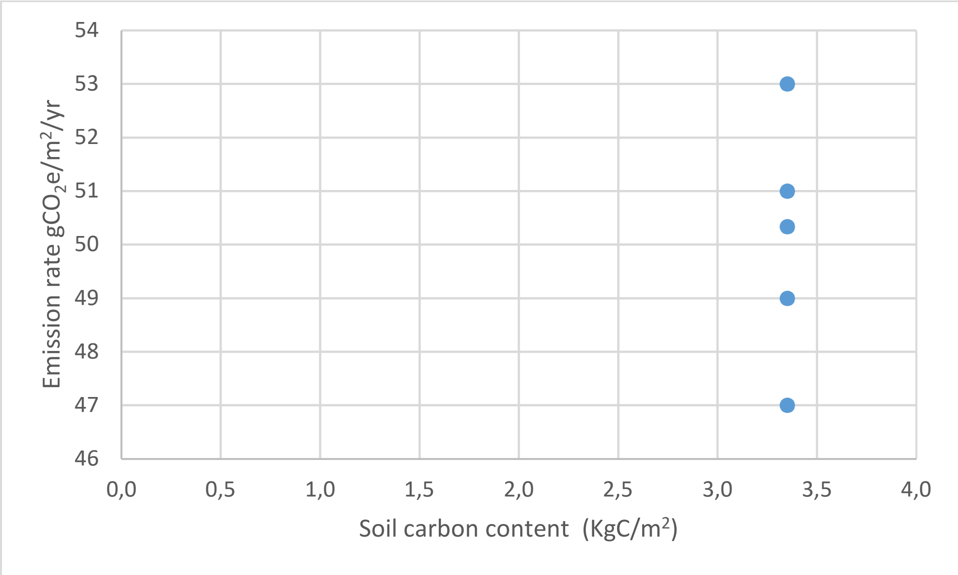


b) Methane

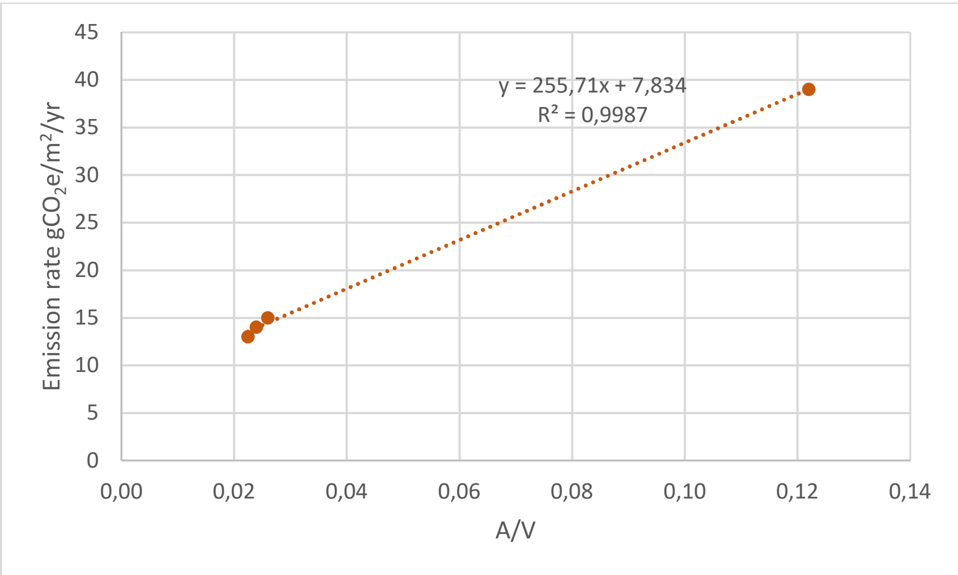


iii. 800-1200 masl

a) Carbon dioxide

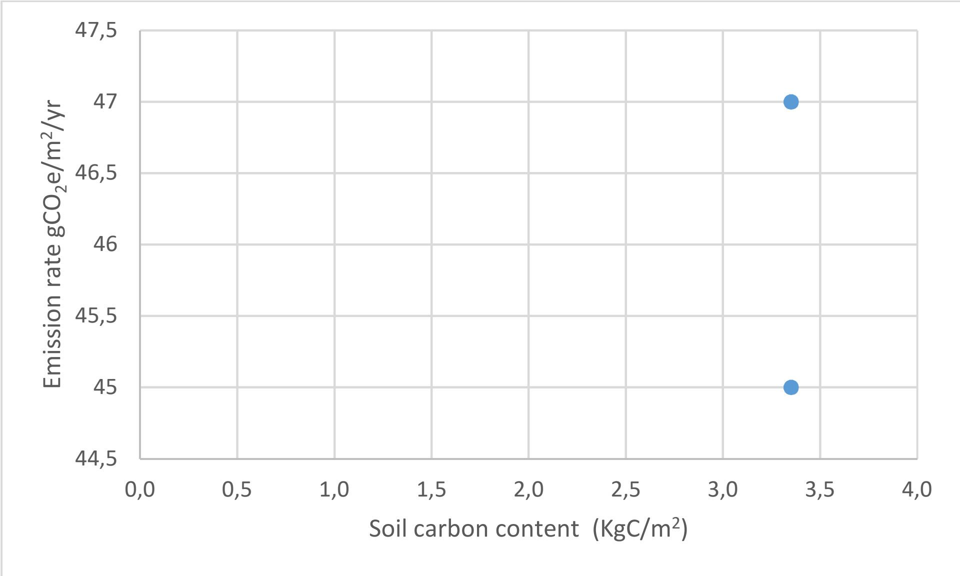


b) Methane

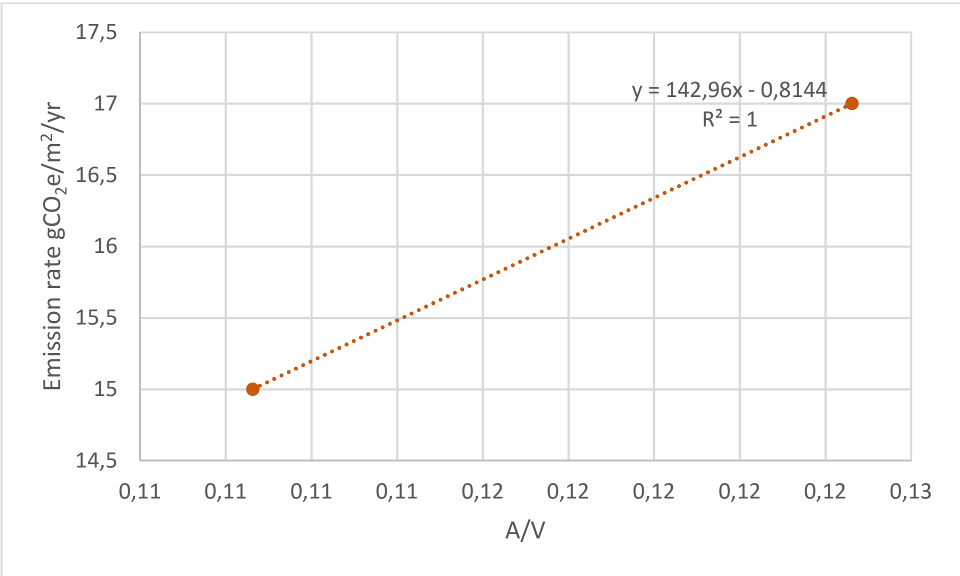


iv. 1200-2200 masl

a) Carbon dioxide



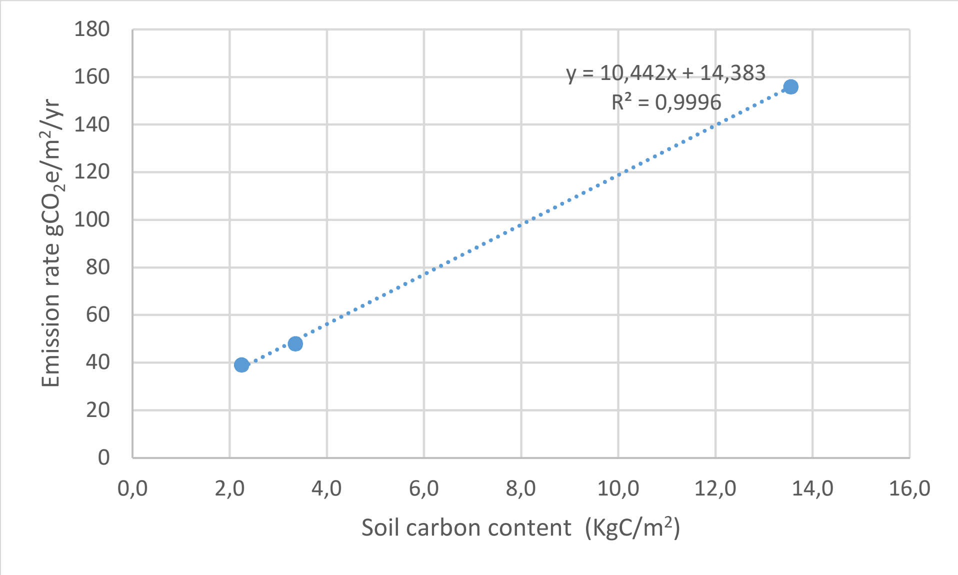
b) Methane



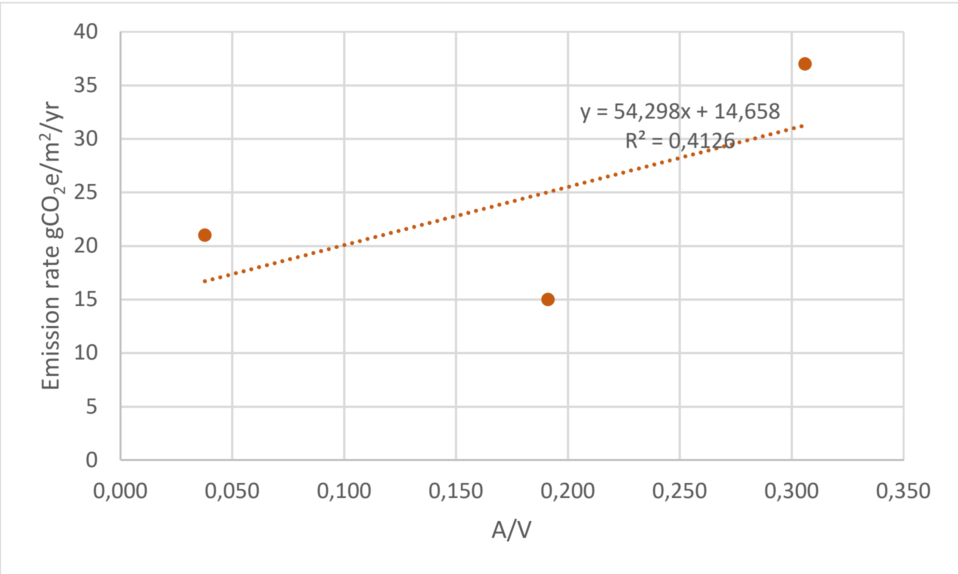
Cold temperate climate zone

i. 0-400 masl

a) Carbon dioxide

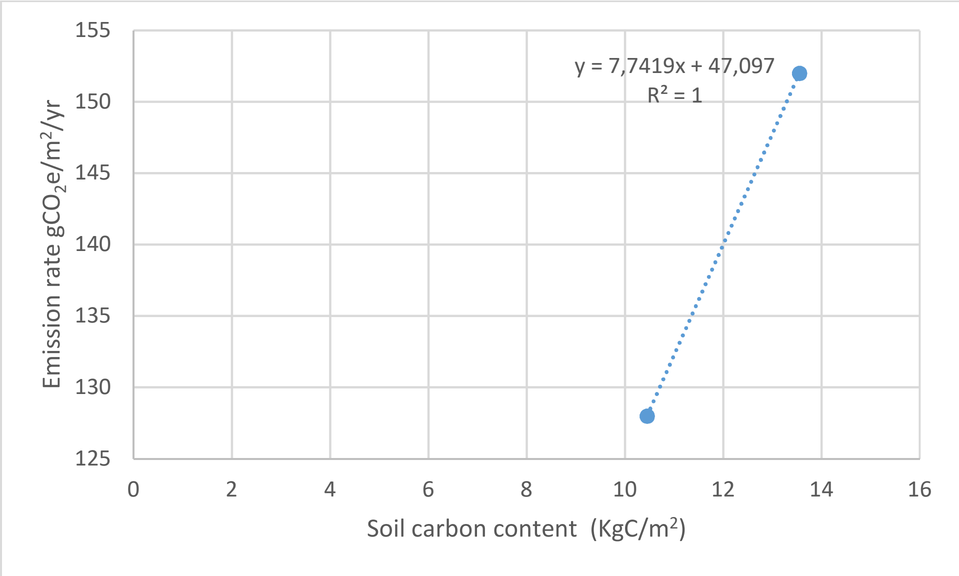


b) Methane

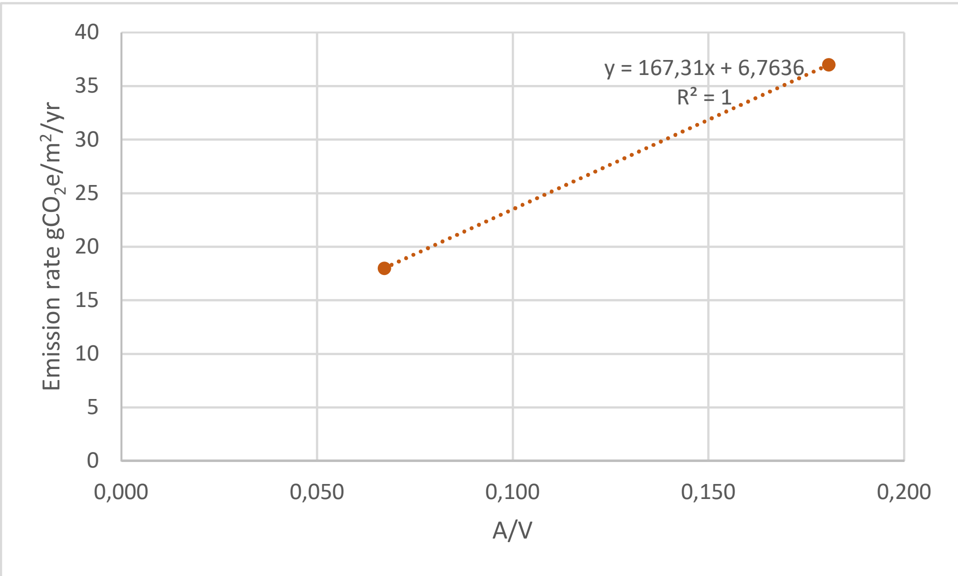


ii. 400-800 masl

a) Carbon dioxide


y = 7,7419x + 47,097
R² = 1
Emission rate gCO2e/m2/yr
155
150
145
140
135
130
125
0 2 4 6 8 10 12 14 16
Soil carbon content (KgC/m2)

b) Methane


y = 167,31x + 6,7636
R² = 1
Emission rate gCO2e/m2/yr
40
35
30
25
20
15
10
5
0
0,000 0,050 0,100 0,150 0,200
A/V

C. Information about the studied Norwegian Reservoirs

Reservoir	LRV	HRV	HRV - LRV	AREAL HRV	Max Depth	MAGVOL MM3	Mean HR	Summer HR	Soil Carbon	A/V
Altevatn	473	489	16	79,7	35,0	1027	2,06	3,90	5,82	0,08
Blåsjø	930,0	1055,0	125,0	80,5	142,0	3105,0	2,31	3,95	3,35	0,03
Buevatna	216,0	226,0	10,0	6,0	10,0	55,3	1,96	3,76	2,86	0,11
Follsjø	375	420	45	6,8	55	179,0	2,31	4,18	3,35	0,04
Fuglevatn	181,0	186,5	5,5	2,8	5,5	14,5	2,00	3,81	2,24	0,19
Gjerdingen	442	449	6,8	3,0	6,8	16,6	2,68	4,53	13,55	0,18
Goringen	66	75	9	2,3	17	7	2,74	4,67	13,55	0,31
Isvatn	1285,0	1295,0	10	1,8	10,0	16,0	2,27	3,91	3,35	0,11
KALHOVDMAGASINET	1075,0	1086,6	11,6	31,3	16,0	256,4	2,55	4,37	3,35	0,12
Kalvatn	521	564	43	28,5	49,0	706	1,92	3,55	3,35	0,04
Kyrkjevatn	1342,0	1352,0	10	0,8	10,0	6,5	2,46	4,27	3,35	0,12
Lundevatn	44,0	48,5	4,5	27,5	12,0	123,0	2,54	4,34	5,56	0,22
Låtervikvatn	868,0	876,0	8	0,4	8,0	2,2	2,31	3,95	3,35	0,16
Nesvatn	493	510	17	17,2	17,0	257	2,59	4,39	10,45	0,07
skarvatn	173,0	179,0	6,0	2,5	12,0	11,3	2,03	3,89	2,24	0,22
SOIKKAJAVRRE	517	529	13	6,5	13,0	61	2,13	4,06	5,83	0,11
Spjodevatn/mjåvatn	153,3	161,8	8,5	3,2	12,0	24,0	2,54	4,35	5,56	0,13
Store fjellvatn	832,8	860,8	28,0	1,3	28,0	17,5	2,24	3,89	3,35	0,07
Storevatn	458	478	20	1,4	20,0	19	2,30	4,03	9,16	0,07
Svartevatn	780	899	119	31,4	130,0	1400	2,31	3,95	3,35	0,02
Sysenvatn	874,0	940,0	66,0	10,4	81,0	436,0	2,27	3,91	3,35	0,02
Teksdalvatn	45,0	49,0	4,0	3,9	8,5	11,0	2,42	4,32	4,32	0,36
Tussevatn	611	656	45	3,3	45,0	107	2,30	4,03	3,35	0,03
Tustervatn-Røssvatn	370,7	383,2	12,5	218,5	20,0	2309,0	1,92	3,55	3,35	0,09

GHG emission with Summer Horizontal radiance as Input

Reservoir	Emission rate tCO2e/yr			Emission rate gCO2e/m2/yr			Total lifetime emission tCO2e
	CO2	CH4	Total	CO2	CH4	Total	
Altevatn	6287	3049	9335	79	38	117	933545
Blåsjø	3781	1192	4974	47	15	62	497368
Buevatna	260	63	323	43	11	54	32270
Follsjø	322	140	462	48	21	68	46227
Fuglevatn	108	41	150	39	15	53	14977
Gjerdingen	456	112	568	152	37	189	56797
Goringen	354	84	438	156	37	194	43789
Isvatn	85	27	112	47	15	62	11177
KALHOVDMAGASINET	1653	1207	2860	53	39	91	286008
Kalvatn	1435	631	2066	50	22	72	206595
Kyrkjevatn	36	14	49	45	17	62	4938
Lundevatn	2076	6096	8172	75	222	297	817195
Låtervikvatn	19	20	39	47	50	97	3885
Nesvatn	2205	306	2511	128	18	146	251072
skarvatn	92	204	296	37	81	118	29582
SOIKKAJAVRRE	505	200	705	78	31	108	70491
Spjodevatn/mjåvatn	241	333	574	75	104	179	57399
Store fjellvatn	63	56	119	48	43	91	11872
Storevatn	150	77	227	107	55	162	22660
Svartevatn	1532	398	1931	49	13	61	193092
Sysenvatn	535	147	683	51	14	66	68265
Teksdalvatn	233	627	861	60	161	221	86057
Tussevatn	155	59	214	47	18	65	21353
Tustervatn-Røssvatn	11097	7463	18560	51	34	85	1855982

GHG emission with Mean Horizontal radiance as Input

Reservoir	Emission rate tCO2e/yr			Emission rate gCO2e/m2/yr			Total lifetime emission tCO2e
	CO2	CH4	Total	CO2	CH4	Total	
Altevatn	6287	2723	9010	79	34	113	900967
Blåsjø	3781	1118	4899	47	14	61	489944
Buevatna	260	60	320	43	10	53	31977
Follsjø	322	126	448	48	19	66	44813
Fuglevatn	108	39	148	39	14	53	14765
Gjerdingen	456	95	551	152	32	184	55074
Goringen	354	63	417	156	28	184	41673
Isvatn	85	25	110	47	14	61	10911
KALHOVDMAGASINET	1653	1015	2668	53	32	85	266815
Kalvatn	1435	596	2031	50	21	71	203112
Kyrkjevatn	36	13	49	45	16	61	4281
Lundevatn	2076	2299	4375	75	84	159	437487
Låtervikvatn	19	16	35	47	41	88	3522
Nesvatn	2205	250	2454	128	15	143	245447
skarvatn	92	131	223	37	52	89	22318
SOIKKAJAVRRE	505	158	663	78	24	102	66297
Spjodevatn/mjåvatn	241	158	399	75	49	125	39917
Store fjellvatn	63	45	108	48	34	83	10781
Storevatn	150	39	189	107	28	135	11853
Svartevatn	1532	376	1908	49	12	61	190820
Sysenvatn	535	138	673	51	14	65	67290
Teksdalvatn	233	354	587	60	91	150	69773
Tussevatn	155	47	201	47	14	61	20146
Tustervatn-Røssvatn	11097	6404	17501	51	29	80	1750118

D. Inputs of Temperature and Wind velocity

Below is the tabulated data on reservoirs measurement station of temperature and wind velocity, their latitude, longitude, wind velocity and temperature in ⁰C.

Reservoir Number	Reservoir Name	Location of measurement station		Measurement station	Wind Velocity (m/s)
		Latitude	Longitude		
1	Buevatn	70.6 N	29.7 E	Båtsfjord-Straumsesakasla	6,85
2	Fuglevatn	70.06 N	29.83 E	Vadså lufthavn	5,57
3	Gorningen	59.2 N	9.6 E	Gjerpen Århus (Temp), Wind velocity (Google earth engine)	5,2
4	Lundevatn	58.42 N	6.17 E	Eik Hov	2,16
5	Skarvatn	71.1 N	23.9 E	Fruholmen Fyr	7,84
6	Spjodevatn/Mjåvatn	58.42 N	6.17 E	Eik Hov	2,16
7	Teksdalvatn	63.7 N	9.6 E	Ørland III	6,03
8	Tustervatn/Røsvatn	65.8 N	14.2 E	Varntresk	3,17
9	Altevatn	69.06 N	18.54 E	Bardufoss	2,23
10	Follsjø	63.05 N	9.09 E	Tågdalen (Temp), Wind velocity (Google earth engine)	6,22
11	Gjerdingen	61.25 N	8.9 E	Beitostølen	3,24
12	Kalvatn	66.4 N	14.3 E	Mo I Rana Lufthavn	2,26
13	Nesvatn	59.03 N	8.5 E	Tveitsund	1,66
14	Soikkajavrre	69.8 N	21.9 E	Nordstraum I Kvænangen	3,88
15	Storevatn	62.03 N	4.99 E	Kråkenes	8,68
16	Svartevatn	59.33 N	6.88 E	Blåsjø	6,31
17	Tussevatn	62.2 N	6.1 E	Ørsta-Lufthamn	1,84
18	Blåsjø	59.33 N	6.88 E	Blåsjø	6,31
19	Kalhovdmagasinet	59.8 N	8.2 E	Møsstrand II	3,91
20	Låtervikvatn	58.9 N	6.9 E	Sirdal–Sinnes	2,18
21	Store fjellvatn	60.86N	6.46E	Myrkdalen-Ondrahaugen (Wind)	4,13
		60.85 N	5.97E	Modalen III (Temperature)	
22	Sysenvatn	60.4 N	7.3 E	Fet I Eidfjord	3,49
23	Isvatn	59.8 N	7.4 E	Vågsli	1,63
24	Kyrkjevatn	61.6 N	7.99 E	Sognefjellhytta	4,33

The numbers in the table below denote the Reservoir number in the table above:

1		2		3		4		5	
Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)
Jan	-6,7	Jan	-6	Jan	-2,3	Jan	0,1	Jan	-0,9
Feb	-6,6	Feb	-5,8	Feb	-0,2	Feb	-0,7	Feb	-1,3
Mar	-4,9	Mar	-3,9	Mar	1,9	Mar	2,6	Mar	-0,6
Apr	-1,7	Apr	-0,4	Apr	5,7	Apr	5,5	Apr	1,5
May	2,8	May	4	May	11	May	9,8	May	4,5
Jun	6,5	Jun	7,8	Jun	15,3	Jun	13,1	Jun	6,7
Jul	10,4	Jul	11,2	Jul	17,2	Jul	15,4	Jul	9,5
Aug	9,6	Aug	10,4	Aug	15,1	Aug	14,3	Aug	9,9
Sep	7,3	Sep	7,9	Sep	12,9	Sep	11,7	Sep	8,9
Oct	1,8	Oct	2,7	Oct	7,3	Oct	7,4	Oct	5,1
Nov	-2,3	Nov	-1,3	Nov	1,5	Nov	3,9	Nov	2
Dec	-4,7	Dec	-3,6	Dec	-0,5	Dec	0,2	Dec	0,6

6		7		8		9		10	
Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)
Jan	0,1	Jan	0,5	Jan	-6,3	Jan	-10,1	Jan	-3,1
Feb	-0,7	Feb	0,7	Feb	-6,4	Feb	-8,1	Feb	-2,6
Mar	2,6	Mar	2,5	Mar	-4,1	Mar	-4,5	Mar	-0,6
Apr	5,5	Apr	5,2	Apr	0,1	Apr	0,5	Apr	2,5
May	9,8	May	9,2	May	4,8	May	6,6	May	6,8
Jun	13,1	Jun	11,6	Jun	9,2	Jun	10,3	Jun	9,8
Jul	15,4	Jul	14,2	Jul	13,3	Jul	13,4	Jul	13,2
Aug	14,3	Aug	14,3	Aug	12	Aug	12	Aug	12,4
Sep	11,7	Sep	11,9	Sep	8,4	Sep	8,3	Sep	9,5
Oct	7,4	Oct	7,5	Oct	2,8	Oct	1,6	Oct	4,5
Nov	3,9	Nov	4,2	Nov	-1,3	Nov	-4,2	Nov	0,5
Dec	0,2	Dec	1,4	Dec	-4,2	Dec	-6,7	Dec	-2,6

11		12		13		14		15	
Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)
Jan	-7,2	Jan	-6,2	Jan	-2,7	Jan	-3,6	Jan	3,6
Feb	-6,2	Feb	-5,5	Feb	-2,6	Feb	-3,7	Feb	3,4
Mar	-3,4	Mar	-2,4	Mar	1,2	Mar	-2	Mar	4,3
Apr	-0,6	Apr	1,9	Apr	4,9	Apr	1,5	Apr	5,7
May	4,3	May	6,9	May	9,5	May	6,2	May	8,5
Jun	8,7	Jun	11,3	Jun	13,6	Jun	9,3	Jun	10,8
Jul	11,4	Jul	14,8	Jul	15,9	Jul	12,4	Jul	13,6
Aug	9,9	Aug	13,3	Aug	14,3	Aug	12	Aug	14,5
Sep	6,8	Sep	9,4	Sep	11,4	Sep	9,2	Sep	12,8
Oct	1,5	Oct	3,6	Oct	6,1	Oct	4,3	Oct	9,7
Nov	-3,1	Nov	-1,1	Nov	2	Nov	0,7	Nov	6,7
Dec	-5,9	Dec	-4,4	Dec	-1,6	Dec	-1,6	Dec	4,3

16		17		18		19		20	
Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)
Jan	-6,7	Jan	-0,1	Jan	-6,7	Jan	-7,2	Jan	-4,3
Feb	-6,4	Feb	0	Feb	-6,4	Feb	-6,6	Feb	-4,5
Mar	-4,4	Mar	2,4	Mar	-4,4	Mar	-3,5	Mar	-1,1
Apr	-2,9	Apr	5,1	Apr	-2,9	Apr	-0,3	Apr	2,1
May	2,7	May	9,1	May	2,7	May	4,4	May	6,8
Jun	5,4	Jun	11,6	Jun	5,4	Jun	8,8	Jun	10,5
Jul	8,7	Jul	14,6	Jul	8,7	Jul	11,4	Jul	13,1
Aug	8,1	Aug	13,9	Aug	8,1	Aug	9,9	Aug	11,9
Sep	6,2	Sep	11,3	Sep	6,2	Sep	7	Sep	9,3
Oct	1,6	Oct	6,4	Oct	1,6	Oct	1,9	Oct	4,6
Nov	-1,8	Nov	3	Nov	-1,8	Nov	-2,2	Nov	0,7
Dec	-4,7	Dec	1,4	Dec	-4,7	Dec	-5,8	Dec	-3,4

21		22		23		24	
Months	Temp(C)	Months	Temp(C)	Months	Temp(C)	Months	Temp(C)
Jan	-1,7	Jan	-5,5	Jan	-7,2	Jan	-9,6
Feb	-1,4	Feb	-5,1	Feb	-6,6	Feb	-9
Mar	1,2	Mar	-2,3	Mar	-3,1	Mar	-7,6
Apr	4,1	Apr	0,8	Apr	0,2	Apr	-4,2
May	8,3	May	5,3	May	4,6	May	0,3
Jun	11,7	Jun	9,1	Jun	8,9	Jun	4
Jul	14,2	Jul	12	Jul	11,6	Jul	7,3
Aug	13,4	Aug	10,7	Aug	10,2	Aug	6,6
Sep	10,8	Sep	8	Sep	7,4	Sep	3,4
Oct	6,3	Oct	3,1	Oct	2,1	Oct	-1,6
Nov	2,6	Nov	-0,8	Nov	-1,9	Nov	-5,4
Dec	-0,7	Dec	-4,1	Dec	-6,1	Dec	-8,6

E. Net emission for reservoirs with field measurement

Laos, Nam Gnouang

Catchment Data:

Catchment Area: 2942 km^2 (ICEM, 2011)

Population in the catchment: 26000

Catchment annual runoff: 1019.4

Community Wastewater Treatment: None

Release of Phosphorus from industrial sewage in the catchment (kg P/yr): 0

Industrial Wastewater Treatment: None

Land Cover in the Catchment Area: based on Nam Khading / Nam Theun and not solely of Nam Gnouang.

Area	%
Cropland	2.3
Bare Areas	0
Wetlands	0
Forest	57.5
Grassland	0.6
Permanent Snow/Ice	0
Settlements	0
Water Bodies	
Drained Peatlands	0
No Data	39

(Sioudom, 2013)

Pre-Impoundment Land Cover in the Reservoir Area:

Reservoir Area: 105 km^2

Area	Mineral Soil%	Organic Soil %
Croplands	56.3	0
Bare Areas	0	0
Wetlands	0	0
Forest	21.1	0
Grassland	0	0
Permanent Snow/Ice	0	0
Settlements	1.5	0
River Area before Impoundment	0.1	
Drained Peatlands		0
No Data	21	

(ICEM, 2011)

River Length before Impoundment (m): 1000

Reservoir Data:

Country: Laos

Longitude of Dam (DD): 104.64

Latitude of Dam (DD): 18.30

Climate Zone (Reservoir Area): Tropical

Impoundment Year: 2011

Reservoir Area (km^2): 105 (at HRWL)

Reservoir Volume (km^3): 2.262

Mean/Normal Operating Level (masl): 438 (based on the mean value of the the difference between HRWL and LRWL)

Maximum Depth (m): 65 (2018a)

Mean Depth (m): 21.543 from the tool based on the input

Littoral Area (%): 9.092 from the tool based on the input

Thermocline Depth (m): 0.6 from the tool based on the input

Water Intake Depth (m): 18

Water Intake Elevation (masl): 420 (LRWL assumed)

Soil Carbon Content under Impounded Area (kgC/m^2): 20 (Assumed to be same as Nam Leuk Reservoir in Lao)

Annual Wind Speed at 10m (m/s): 2.06

Water Residence Time (WRT, yrs): 0.7542

Annual Discharge from the Reservoir (m^3/s): 95.1

Phosphorus Concentration (µg/L): 9 (modified)

Trophic Level: Oligotrophic

Reservoir Mean Global Horizontal Radiance ($kWh/m^2/d$): 4.71

Mean Temperature per Month(ºC)

Month	ºC
Jan	26.33
Feb	29
Mar	35
Apr	36.67
Mai	36.33
Jun	34
Juli	31.67
Aug	31.33
Sept	31
Oct	31
Nov	30.33
Dec	27

Mean Annual Air Temperature: 31.6 ºC

Reservoir Services Data:

Hydroelectricity: Primary: 100%

Capacity (MW):

Total annual Generation (GWh/yr): 294

Construction GHG:

Concrete: 480000 m^3

Equipment:

Power Generation: 60 MW

Power Connection: 115 kV, 55 km length

***Albania, Banja**:*

Catchment Data:

Catchment Area: 2890 km^2

Population in the catchment: 12000

Catchment annual runoff: 1149

Community Wastewater Treatment: None

Release of Phosphorus from industrial sewage in the catchment (kg P/yr): 0

Industrial Wastewater Treatment: None

Land Cover in Catchment Area

Area	%
Cropland	19
Bare Areas	8
Wetlands	0
Forest	29
Grassland	27
Permanent Snow/Ice	0

Settlements	12
Water Bodies	5
Drained Peatlands	0
No Data	0

Pre-Impoundment Land Cover in the Reservoir Area:

Reservoir Area (km^2): 14

Area	Mineral Soil%	Organic Soil %
Croplands	10	0
Bare Areas	13	0
Wetlands	0	0
Forest	4	0
Grassland	23	0
Permanent Snow/Ice	0	0
Settlements	0	0
River Area before Impoundment	25	
Drained Peatlands		0
No Data	25	

Reservoir Data:

Country: Albania

Longitude of Dam (DD): 40.71

Latitude of Dam (DD): 20.84

Climate Zone (Reservoir Area): Tropical

Impoundment Year: 2016

Reservoir Area (km^2): 14

Reservoir Volume (km^3): 0.178

Mean/Normal Operating Level (masl): 168

Maximum Depth (m): 80

Mean Depth (m): 12.714

Littoral Area (%): 18.313

Thermocline Depth (m): 0.9

Water Intake Depth (m): 8

Water Intake Elevation (masl): 160

Soil Carbon Content under Impounded Area (kgC/m^2): 4.8

Annual Wind Speed at 10m (m/s): 2

Water Residence Time (WRT, yrs): 0.0536

Annual Discharge from the Reservoir (m^3/s): 105.3

Phosphorus Concentration (µg/L): 35.7

Trophic Level: Eutrophic

Reservoir Mean Global Horizontal Radiance (kWh/m^2/d): 4.11

Mean Temperature per month (^{o}C)

Month	Temperature (^{o}C)
January	0
February	2.0
March	5.0
April	9.5
May	14.5
June	17.5
July	19.5
August	18.5
September	15.0
October	10.0

November	5.0
December	2.0

Mean Annual Air Temperature (ºC): 9.9

Reservoir Services Data:

Hydroelectricity: Primary: 100%

Capacity (MW): 72

Total annual Generation (GWh/yr): 255

Construction GHG:

Earth and Rockfill: 4 458 600 m^3

Roads and Bridges:

Refurbishment of existing road: 26.9 km

Equipment:

Power Generation: 72 MW

Power Connection: 110 kV, 12 km length

Norway, Follsjø :

Catchment Data:

Catchment Area: 554 km^2

Population in the catchment: 0

Catchment annual runoff: 10717.7

Community Wastewater Treatment: None

Release of Phosphorus from industrial sewage in the catchment (kg P/yr): 0

Industrial Wastewater Treatment: None

Land Cover in Catchment Area:

Area	%

Cropland	0
Bare Areas	66.3
Wetlands	4.7
Forest	13.4
Grassland	0
Permanent Snow/Ice	0.4
Settlements	0
Water Bodies	5.9
Drained Peatlands	0
No Data	9.3

Pre-Impoundment Land Cover in the Reservoir Area:

Reservoir Area (km^2): 6.75

Area	Mineral Soil%	Organic Soil %
Croplands	0	0
Bare Areas	0	0
Wetlands	8.8	0
Forest	47.13	0
Grassland	0.04	0
Permanent Snow/Ice	0	0
Settlements	0	0
River Area before Impoundment	6.5	
Drained Peatlands	0	
No Data	37.75	

Reservoir Data:

Country: Norway

Longitude of Dam (DD): 62.96

Latitude of Dam (DD): 9.11

Climate Zone (Reservoir Area): Boreal

Impoundment Year: 1968

Reservoir Area (km^2): 6.75

Reservoir Volume (km^3): 0.179

Mean/Normal Operating Level (masl): 398

Maximum Depth (m): 55

Mean Depth (m): 26.519

Littoral Area (%): 5.846

Thermocline Depth (m): 9.6

Water Intake Depth (m): 23

Water Intake Elevation (masl): 375

Soil Carbon Content under Impounded Area (kgC/m^2): 3.35

Annual Wind Speed at 10m (m/s): 2.21

Water Residence Time (WRT, yrs): 0.0301

Annual Discharge from the Reservoir (m^3/s): 188.3

Phosphorus Concentration (µg/L): 1.8

Trophic Level: Oligotrophic

Reservoir Mean Global Horizontal Radiance ($kWh/m^2/d$): 4.18

Mean Temperature per month (ºC)

Month	Temperature (ºC)
January	-4.7
February	-2.2
March	-0.8

April	4.1
May	7.6
June	10.9
July	11.7
August	10
September	6.6
October	1
November	-1.9
December	-3.9

Mean Annual Air Temperature (ºC) 3.2

Reservoir Services Data:

Hydroelectricity: Primary: 100%

Capacity (MW): 127

Total annual Generation (GWh/yr): 805

Construction GHG:

Earth and Rockfill: 1300000 m^3

Concrete: 680 m^3

Equipment:

Power Generation: 126.6 MW

Power Connection: 22 kV

Norway, Svartevatn :

Catchment Data:

Catchment Area: 208.2 km^2

Population in the catchment: 0

Catchment annual runoff: 2891.85

Community Wastewater Treatment: None

Release of Phosphorus from industrial sewage in the catchment (kg P/yr): 0

Industrial Wastewater Treatment: None

Land Cover in Catchment Area:

Area	%
Cropland	0
Bare Areas	73.8
Wetlands	4.4
Forest	0.2
Grassland	0
Permanent Snow/Ice	0
Settlements	0
Water Bodies	21.6
Drained Peatlands	0
No Data	0

Pre-Impoundment Land Cover in the Reservoir Area:

Reservoir Area (km^2): 31.4

Area	Mineral Soil%	Organic Soil %
Croplands	0	0
Bare Areas	100	0
Wetlands	0	0
Forest	0	0
Grassland	0	0
Permanent Snow/Ice	0	0
Settlements	0	0
River Area before Impoundment	0	

Drained Peatlands	0
No Data	0

Reservoir Data:

Country: Norway

Longitude of Dam (DD): 59.13

Latitude of Dam (DD): 6.89

Climate Zone (Reservoir Area): Boreal

Impoundment Year: 1976

Reservoir Area (km^2): 31.4

Reservoir Volume (km^3): 1.4

Mean/Normal Operating Level (masl): 840

Maximum Depth (m): 130

Mean Depth (m): 44.589

Littoral Area (%): 5.374

Thermocline Depth (m):_

Water Intake Depth (m): 60

Water Intake Elevation (masl): 780

Soil Carbon Content under Impounded Area (kgC/m^2): 3.35

Annual Wind Speed at 10m (m/s): 6.37

Water Residence Time (WRT, yrs): 2.3243

Annual Discharge from the Reservoir (m^3/s): 19.1

Phosphorus Concentration (µg/L): 3.2

Trophic Level: Oligotrophic

Reservoir Mean Global Horizontal Radiance ($kWh/m^2/d$): 3.95

Mean Temperature per month (^oC)

Month	Temperature (ºC)
January	-6.7
February	-6.4
March	-4.4
April	-2.9
May	2.7
June	5.4
July	8.7
August	8.1
September	6.2
October	1.6
November	-1.8
December	-4.7

Mean Annual Air Temperature (ºC) 0.5

Reservoir Services Data:

Hydroelectricity: Primary: 100%

Capacity (MW): 200

Total annual Generation (GWh/yr): 2923

Construction GHG:

Earth and Rockfill: 4700000 m^3

Concrete: 680 m^3

Equipment:

Power Generation: 200 MW

Power Connection: 300 kV

F. Results of Net GHG emission for the reservoirs with field measurement using G-Res tool

Reservoirs	Emission	Emission rate tCO2e/yr			Emission rate gCO2e/m2/yr			Life time emision tCO2e
		CO2	CH4	Total	CO2	CH4	Total	Total
Follsjø	Post-Impoundment	301	140	441	45	20	65	44129
	Pre-Impoundment	-127	8	-120	-18	0	-18	-11960
	UAS	0	0	0	0	0	0	0
	Net GHG	428	118	547	63	20	83	
	Construction			309				30908
	Final Net GHG			870	63	20	83	86997
Svartevatn	Post-Impoundment	1531	398	1931	49	13	61	193092
	Pre-Impoundment	0	0	0	0	0	0	
	UAS	0	0	0	0	0	0	
	Net GHG	1532	398	1931	49	13	61	193092
	Construction			2189				218938
	Final Net GHG			4120				412030
Banja	Post-Impoundment	758	1832	2590	54	131	185	259008
	Pre-Impoundment	-78	62	-16	-6	4	-1	-1604
	UAS	0	0	0	0	0	0	0
	Net GHG	837	1769	2606	60	126	186	
	Construction			1452				145235
	Final Net GHG			4058	60	126	186	405848
Nam Gnouang	Post-Impoundment	53221	197777	250998	507	1884	2390	25099790
	Pre-Impoundment	-3102	3	-3099	-30	0	-30	-309856
	UAS	0	0	0	0	0	0	0
	Net GHG	56322	197774	254096	537	1884	2420	
	Construction			2052				205232
	Final Net GHG			256148	536	1884	2420	25614877