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Model for ROV and Operation Comparison

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1 Executive Summary

This paper includes documentation and emission results for three seperate case studies which has been formulated in a collaboration between IKM Subsea AS, Avito and Terravera. The first case aims to estimate differences in the operational emissions for two ROV's with electric and hydraulic thruster systems. In this case output power, general efficiencies for the two separate systems, specific losses, emission intensities as well as other factors has been taken into account to produce emission estimates for the two ROV's in two distinct operational modes. The findings indicate that using an electric ROV instead of a hydraulic ROV can save 4.2 - 28.6 kgCO2/h depending on the operation and energy supply. Also, using a hydraulic ROV instead of an electric ROV would entail an increase in emissions of 32.6%-35.9% per hour. These findings reflect the relative operation emissions, while emission from production, transportation, maintenance and end-of-life is currently not included. The second case examined has looked into the emissions from winch operation using a traditional WROV and an IKM RROV. The main difference between between these two alternatives in this case is the hoist frequency required. For the traditional WROV a hoist frequency of 5 times per week has been used, while for the IKM RROV a hoist frequency of 1 time per 3 months has been used. The findings indicate that when the energy supply is from gas turbines on rig the emission for the traditional WROV and IKM RROV is 469.11 kgCO2/quarter and 7.82 kgCO2/quarter, respectively. When the energy supply is based on onboard diesel engines on a vessel the emission are 1183.86 kgCO2/quarter and 19.72 kgCO2/quarter, for the traditional WROV and IKM RROV respectively. The unit used here is given per quarter as the calculations has been done for a three month interval. The final case study examined in this project has been to compare emission when using an onshore control room vs and offshore control room. In this case the main emissions comes from transportation to each different control room, as well as emission from food transportation and energy consumption. The case has looked at several different types of residence cities and transportation alternatives. However the results indicate that using an onshore control room has significantly lower emission compared to using offshore control rooms, by a factor of ∼10.

The calculations and datapoints described in this paper has been implemented in a model in Terravera's platform and can be accessed using this link. The model has been designed to allow for scenario analyses and to include more in depth emission in the future.

2 Introduction

This paper describes detailed information and documentation in relation to an environmental model developed by the Terravera Foundation. The model is developed in collaboration with Avito and IKM Subsea AS and examines the envirnonmental performance of some of IKM Subsea AS's Remotely Operated Vehicles (ROV) and its operations. Sufficient information and context for understanding the underlying model and calculations are presented in the paper, while some additional calculation context is provided in the appendix. For additional contex for calculation, please contact current Sustainability Modelling Lead at Terravera, Andreas Jørgensen.

2.1 Problem Description and Scope

The model developed and this paper describes in essence three seperate problems; Emission comparison between **Electric vs Hydraulic ROV**, emission comparison between **Use of Traditional vs IKM ROV** and and emission comparison between **On-shore vs off-shore control room**. What these three problem descriptions have in common that they all reflect different aspects of IKM Subsea's operational alternatives. Further context for each of the separate problem descriptions will be further explained in the following sections.

On a general basis, the scope of the model only includes the operational emissions in each case. Thus, this analysis is not a full Life Cycle Analysis (LCA) which would have included emissions in production, transport and end-of-life stages. Additionally, since all three cases is a comparison between two separate alternatives each, common emissions observed for both alternatives is generally not included. Thus, results should be viewed as relative instead of absolute. Examples of this can for example be viewed in the case where Electric and Hydraulic ROV is compared. Emissions from common components found in both ROV's is not included in the emission calculations, while emission from components which differ between the two ROV's is included for components where emissions data is available.

2.1.1 Electric vs Hydraulic ROV

This specific part of the project aimed to examine the difference in operational energy use and emission, based on what type of ROV used. IKM deploys ROV's full electric ROV as well as ROV's with major hydraulic elements. For the electric ROV one large, main motor drives the different hydraulic pumps on the ROV, which in turn drives the thrusters. For the electric ROV, smaller electric motors directly power each thruster. The scope of this part of the project only includes the operational phase of the ROV's, thus emissions from production, component differences and end-of-life is not taken into account.

2.1.2 Use of Traditional vs IKM ROV

This use-case depicts the difference in emission between the traditional ROV and IKM ROV, taking into account the frequency with which they need to be hoisted from the sea. The frequency of hoisting for the ROVs significantly differs, as the conventional ROV necessitates winching five times per week, whereas the IKM ROV requires it only once every three months. This use-case focuses on the emissions related to operating the winch at different frequencies on both an offshore platform, as well as on maritime vessels.

2.1.3 Onshore vs Offshore Control Room

This sub-project aims to examine the differences in emission when an onshore control room is used instead of an offshore control room. In the case for onshore control room, operators needs to travel by car from Stavenger to Bryne. While for the offshore control room case operators are assumed to travel from Oslo or Bergen to Florø, to then be transported out to the SnorreB oil platform by helicopter. Cases where operators reside in Oslo and Bergen has also been included.

3 Model Description

The data gathered and calculations has been implemented in a model i the Terravera ecosystem. Since this project doesn't aim to model a value chain, some alternative approaches for designing the model needed to be made. First of all, all three sub-projects of this project with Avito and IKM is included in the same model. Generally for the model, main stages for calculation has been included as "processes", in order to make the approach more visual. For the case **Electric vs Hydraulic ROV** and **Use of Traditional vs IKM ROV** the power consumption form the basis of the sub-model, which is then converted to emissions. For the **Onshore vs Offshore Control Room**, the transport stages has been included for each scenario.

As for the datasets the most important datapoints have been included. This means that some small calculations or conversions are not included. For a full overview of all data used in this project a separate excel file will contain all data and calculations.

The indicators are separated by which sub-project the results are calculated for. As well as including results that are relevant. A visualisation of the model structure can be seen in figure 1 and the model in Terralight can be accessed here.

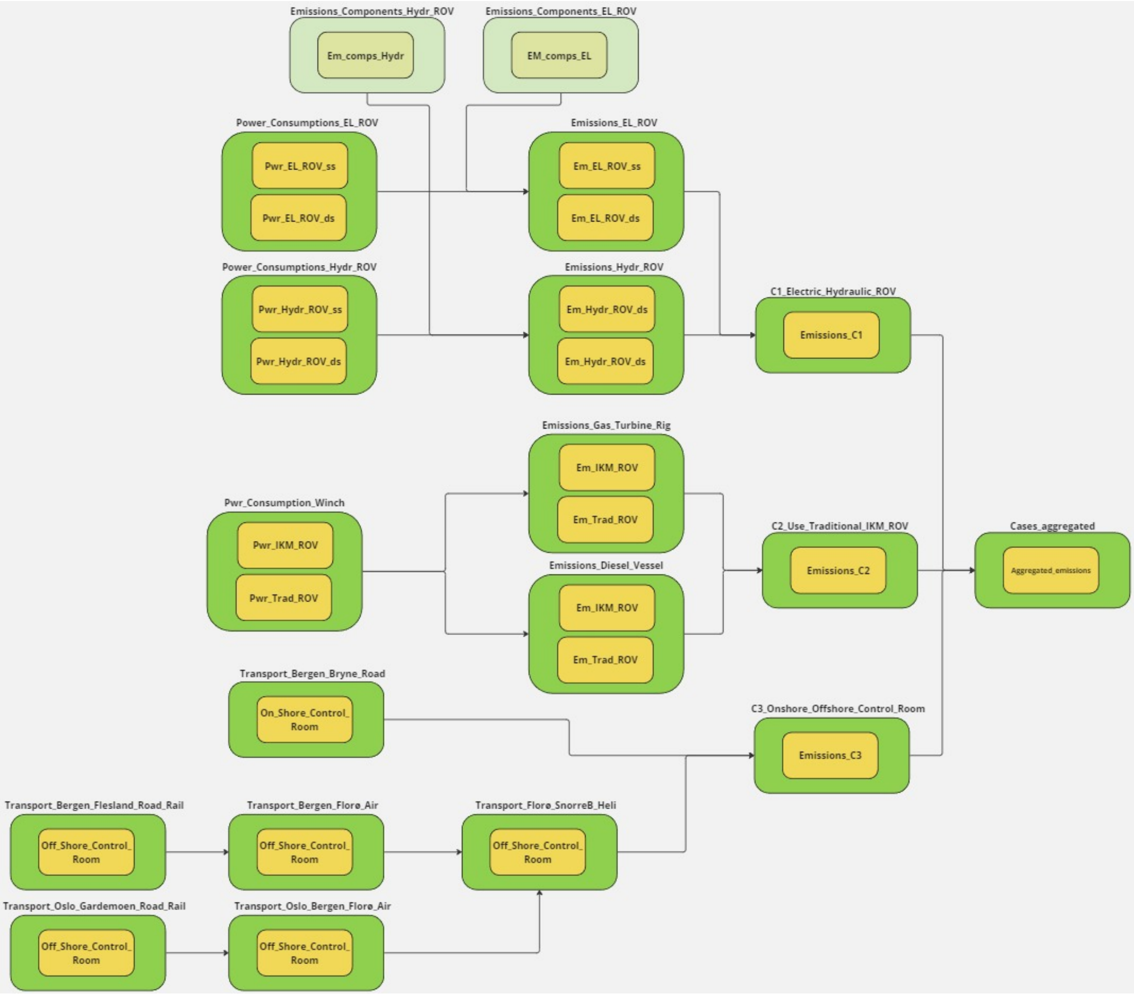

Figure 1: Visualisation of the model. Note: Components for case 1 inlcuded in the model, however data is not yet added in this section.

4 Calculation approach and assumption

This section includes descriptions of calculation approaches, as well as which assumptions have been made for each separate case. This section includes a more general description, more detailed calculation descriptions may be found in the appendix.

4.1 Electric vs Hydraulic ROV

This case focuses on differences in energy consumption and emissions between two similar ROV's with different thruster mechanism. The two mechanism include thrusters powered by electrical motors and thrusters power by hydraulic pumps. For context, both ROVs are supplied with HV Three Phase AC from either an oil rig or support vessel. In the case of the Hydraulic ROV, a large electrical motors powers the hydraulic pumps, which further powers the onboard thrusters on the ROV. The main reason for comparing these ROV's when they are both powered by electricity is to examine differences in energy consumption under operations. The main advantages of electro-motors on the Electric ROV is that for cases with zero thruster load they don't consume energy and electric systems generally have higher efficiencies of energy transfer compared to alternative systems. In the case of the Hydraulic ROV while in operation, the hydraulic pump almost always needs to be powered on a base level (”idle”), consuming energy even with zero load on the thrusters.

In order to estimate operational emissions for each ROV type, the rated power and load for motors located on the ROV needs to be known. Knowing this, losses caused by topside equipment may be calculated which in turn provides the power needed to be supplied by the rig/vessel. Below is a summary of the different electric engines used for each ROV, as well as which topside components are used for each ROV.

	Hydraulic ROV		**Electronic ROV**
1 x Main Electro Motor, 160kW		7 x Off-Electro Motor, 14kW	
Transformer 400VAC-3000VAC		Transformer 400VAC-3000VAC	
Tether		Frequency Converter	
Umbilical Type 1		Sinusoidal Filter	
	3 x 10mm, 4.5kV	Tether	
	2 x 0.82mm, 4.5kV	Umbilical Type 2	
	Fibre Optic Element, 12SM		2 x 1.5mm, 3.3kV
			41 x 2mm, 4.5kV
			Fibre Optic Element, 12SM

Table 1: Equipment overview for electric and hydraulic ROV

4.1.1 Power and Emission Calculations

In order to calculate the emissions in the operation phase of the ROV's, the consumed power needs to be known. In conversations with IKM the max power used for propulsion for both ROV's is set at **100kW**. Two typical operational modes, with different work loads on the thrusters, which is performed by most WROVs in the world are Seabed/pipeline survey and Drill Support. Seabed survey is associated with high degree of flying at constant speed, typically full thrust 90% of the time, and no thrust 10% of the time. Drill support operations are usually associated with high frequencies of flying on/off, typically no thrust 25% of the time, low thrust 50% of the time, and full thrust 25% of the time. Under the scenario *low thrust*, thruster load is assumed to be 30%, while under the scenarios no thrust and full thrust the loads is assumed to be 0% and 100% respectively (for the electric ROV). **In the case of the hydraulic ROV, a constant baseline power consumption or idle power consumption is required under the no thrust scenario, where a base load of 9.96 kW or 9.96% of max thruster load is used. The basis for this the idle power load is presented in equation 2 and 3**

$$n = \frac{q_v \cdot 1000}{\eta_v \cdot V_g} = 1600rpm \rightarrow V_g = \frac{q_v \cdot 1000}{\eta_v \cdot 1600rpm} = \frac{200L \cdot 1000}{0.9 \cdot 1600rpm} = 130.2cm^3 \tag{1}$$

$$T = \frac{130.2cm^3 \cdot 25bar}{2\pi \cdot 0.90 \cdot 10} = 59.5Nm \tag{2}$$

$$P_{idle} = \frac{59.5Nm \cdot 1600rpm}{9.5488} = 9.96kW \tag{3}$$

Further in order to achieve the relative efficiency of the two thruster systems several electric and hydraulic thruster systems has been examined. Based on documentation from Sub-Atlantic on two thruster systems, one electric thruster rated 22kW and 350kg max thrust, and the SA-300 Hydraulic thruster where 350kg thrust is achieved at 240 bar of pressure. In addition, pressure loss in hydraulic valves has been estimated, where stated loss was 70 bar at 77LPM, assuming a linear relationship the estimated loss at 56LPM was ~50bar. Using the same power formula as in equation 3 the power required to achieve 350kg thrust for the SA-300 thruster can be found.

$$P_{SA-300,350kg} = \frac{240bar + 50bar}{0.9 \cdot 600} = 30.1kW \tag{4}$$

This means that for the electric thruster system and the hydraulic SA-300 thruster system to achieve a thrust of 350kg they require 22kW and 30.1kW of power respectively. This means that the hydraulic SA-300 system requires roughly 1.37 times more power compared to the electric system. Further, losses in electric motors, transformers, sinusoidal filters and frequency converters has been included, and is visualised in figure 2

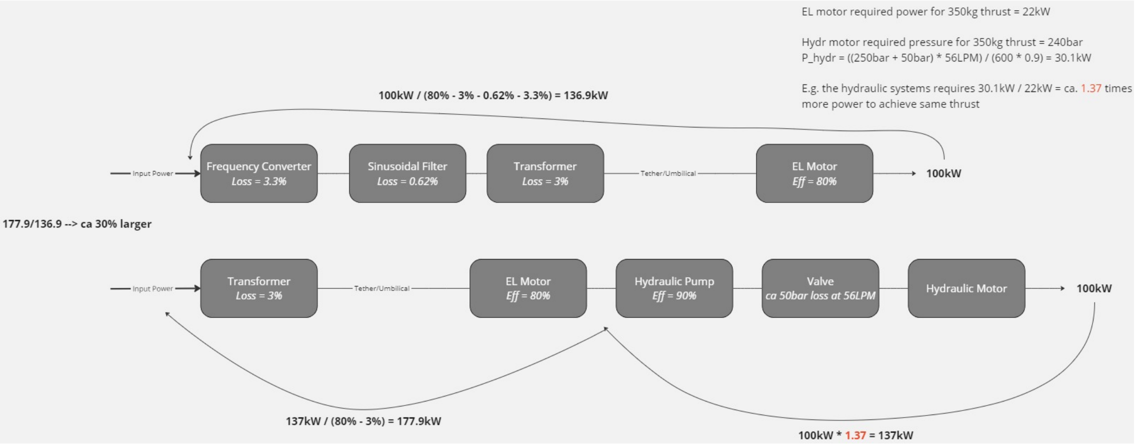

Figure 2: Visualisation of power required for each seperate thuster system

Using the findings above calculating the power consumption of the two ROV's in the two different operations is pretty straight forwards and shown in equation 5, 6, 7 and 8. For context, SS = Seabed Survey, DS = Drill Support, λ = share of time in specific scenario.

$$P_{load,EL,SS} = P_{max} \cdot [(Load \cdot \lambda)_{NoThrust} + (Load \cdot \lambda)_{FullThrust}] \tag{5}$$

$$P_{load,EL,DS} = P_{max} \cdot [(Load \cdot \lambda)_{NoThrust} + (Load \cdot \lambda)_{LowThrust} + (Load \cdot \lambda)_{FullThrust}] \tag{6}$$

$$P_{load,Hydr,SS} = P_{load,EL,SS} \cdot 1.37 + \lambda_{NoThrust} \cdot 9.96kW \tag{7}$$

$$P_{load,Hydr,DS} = P_{load,EL,DS} \cdot 1.37 + \lambda_{NoThrust} \cdot 9.96kW \tag{8}$$

Using this information in combination with equation 5 and 6 the power consumption of the two ROV's during the two seperate operations can be calculated, and is shown in table 2.

Seabed Survey					
	P_{max} [kW]	$(Load \cdot \lambda)_{No\ Thrust}$	$(Load \cdot \lambda)_{Low\ Thrust}$	$(Load \cdot \lambda)_{Full\ Thrust}$	**P_{Load} [kW]**
Electric ROV	100	$0 \cdot 0.1$	$0.5 \cdot 0$	$1 \cdot 0.9$	**90**
Hydraulic ROV	100	$0.0996 \cdot 0.1$	$0.5 \cdot 0$	$1 \cdot 0.9$	**124.03**
Drill Support					
	P_{max} [kW]	$(Load \cdot \lambda)_{No\ Thrust}$	$(Load \cdot \lambda)_{Low\ Thrust}$	$(Load \cdot \lambda)_{Full\ Thrust}$	**P_{Load} [kW]**
Electric ROV	100	$0 \cdot 0.25$	$0.5 \cdot 0.3$	$1 \cdot 0.25$	**40**
Hydraulic ROV	100	$0.0996 \cdot 0.25$	$0.5 \cdot 0.3$	$1 \cdot 0.25$	**57.17**
$\Delta P_{Load,\ SS}$					**34.03 kW**
$\Delta P_{Load,\ DS}$					**17.17 kW**

Table 2: Comparison of load power for electric and hydraulic ROV in seabed survey and drill support operations

Included for both ROV's is the electric motor efficiency. The efficiency used is 80% as this is a quite common efficiency observed for a vast range of electric motors (Jamborowicz 2020, Energy n.d, Nagal 2023). Also included are transformer losses at 3% as stated in the tranformers datasheet. For the electric ROV, losses in sinusoidal filters and frequency converters needs to be included as well, from the datasheet for the sinusoidal filter and frequency converter a loss of 0.62% and 3.3% of rated power was calculated, respectively. When including these losses, as well as the stated efficiencies, the delivered power can be calculated. Multiplying this with the emission intensities from gas turbines (rig supply) and diesel (vessel supply), 0.212 kgCO2/kWh and 0.71325 kgCO2/kwh respectively, emission for both ROV's in both operations can be found. The context for these emission intensities is explained further in section 4.2. The equations below summarise the delivered power and table 3 summarises the emission results.

$$P_{del,EL,SS} = \frac{90kW}{80\% - 5\% - 0.62\% - 3.3\%} = 123.22kW \tag{9}$$

$$P_{del,Hydr,SS} = \frac{124.03kW}{80\% - 5\%} = 161.07kW \tag{10}$$

$$P_{del,EL,DS} = \frac{40kW}{80\% - 5\% - 0.62\%.3\%} = 54.76kW \tag{11}$$

$$P_{del,Hydr,DS} = \frac{57.17kW}{80\% - 5\%} = 74.25kW \tag{12}$$

Emissions results			
Electrical ROV	Rig Supply	Vessel Supply	Unit
Seabed survey	26.12	87.89	kgCO2/h
Drill support	11.61	39.06	kgCO2/h
Hydraulic ROV	Rig Supply	Vessel Supply	Unit
Seabed survey	34.22	115.14	kgCO2/h
Drill support	15.77	53.07	kgCO2/h
Saved emission from using EL ROV			
	Rig Supply	Vessel Supply	Unit
Seabed survey:	8.10	27.25	kgCO2/h
Drill support	4.16	14.01	kgCO2/h
Percentage increase **[increase in emission if using Hydr ROV]**			
	Rig Supply/Vessel Supply		
Seabed Survey	31.0%		
Drill Support	35.86%		

Table 3: Emission results based on ROV type and operation mode.

From table 3 it can be observed that 8.10-27.25 kgCO2/h of operation can be saved by using the electric ROV in the seabed survey operation. During drill support the potential savings are less, at 4.16-14.01 kgCO2/h of operation. Choosing to use the hydraulic ROV would entail increases in emission of 31.0% or 35.86% for seabed survey and drill support respectively, when compared to electric ROV. These differences observed comes mainly from the difference in efficiencies for the two systems as well as the idle power consumption for the hydraulic ROV.

For added context, it is important to mention that these results as relative results. The focus in this specific project has been to examine the main differences in emission for the two types of ROV's during operation. Production, transportation, maintenance and end-of-life emission has not been included. In addition, losses in umbilical and tether has been assumed equal for both the electric and hydraulic ROv, and thus not included in the calculations. We have high confidence in the relative values presented here, but these values does not necessarily represent the absolute or total emissions during operation. In order to estimate these absolute results, a deeper examination into all relevant emission areas and equipment losses for both ROV's needs to be conducted.

4.2 Use of Traditional WROV vs IKM Resident ROV

The methods for supplying electrical power to the winch, responsible for raising and lowering the ROVs, was important in assessing emissions related to the use-case. As per information provided from IKM, the calculations are done using a gas turbine for the winch on offshore platforms, and a diesel generator for the winch on ships.

The operation depth of the ROVs in this use-case was 500 m. With the winch typically hoisting at a speed of 2 m/s, this meant that the winch is in use for 250 s during one lift. With the ROV being neutrally buoyant, the apparent weight the winch would have to lift is that of the tether management system (TMS). With the dimensions provided, the calculations were done considering IKMs Merlin UCV with a weight of 3 tonnes, giving the TMS a weight of 4 tonnes. Using the equation for power in equation 13 with power being the product of force and displacement divided by time, the power required to move the ROV was calculated to **78.48 kW**.

$$P = \frac{Fs}{t} \tag{13}$$

4.2.1 On rig - gas turbine

Based on available literature (Ipieca 2022, Fossil Energy and Management n.d and Boyce 2006), the calculations were done with a gas turbine efficiency of 30%. This is an assumption as we do not know the specifics of the gas turbine used, and as the power needed from the turbine depends on the efficiency it is assumed that while giving a good estimate, the calculations may not precisely represent the reality. Based on Svendsen et al. 2022 and SSB 2017, the emission factor for the gas turbine used was 2.34 kgCO_2/Sm^3. According to a conversion calculator from Norwegian Petroleum n.d, 1 Sm^3 of gas equals 11.11 kWh. From the power required to moving the ROV, the efficiency of the turbine, and the time the winch was in use, the energy needed from the gas turbine is 18.17 kWh. The emission from the gas turbine from one lift is thus calculated to 3.85 kgCO_2. Multiplying with the frequency of winch use gives **462 kg**CO_2 emitted from the traditional ROV, and **7.7 kg**CO_2 emitted from IKMs RROV, for every three months.

CO_2 emission comparison every 3 months - gas turbine	
Traditional ROV	462 kgCO_2
IKM ROV	7.7 kgCO_2

Table 4: Comparison of CO_2 emission every 3 months for the traditional ROV vs IKM RROV with gas turbine

4.2.2 On vessel - diesel generator

As with the gas turbine, the specifics of the diesel generator(s) are not known so some assumptions and generalizations had to be made.

An efficiency rating of 40% for the diesel generator was used in the calculations based on literary findings (Copenhagen Center on Energy Efficiency n.d and General Power n.d). Based on this, the energy needed from the generator is 13.6 kWh. With a specific fuel consumption of

225 $\mathrm{g_{diesel}}$/kWh (Sustainable Ships n.d and Volker-Quasching 2022) and an emission factor of 3.17gCO_2/$\mathrm{g_{diesel}}$ (SSB 2017), the emission from one lift becomes:

$$225\frac{g_{diesel}}{kWh} * 13.6kWh * 3.17\frac{gCO_2}{g_{diesel}} = 9.7kgCO_2 \tag{14}$$

Multiplying the CO_2 emitted from one lift with the frequency of the winch usage gives an emission of **1166 kg**CO_2 for the traditional ROV, and **19.43 kg**CO_2 for the IKM RROV.

CO_2 emission comparison every 3 months- diesel generator	
Traditional ROV	1166 kgCO_2
IKM ROV	19.43 kgCO_2

Table 5: Comparison of CO_2 emission every 3 months for the traditional ROV vs IKM RROV

The results in table 5 are the one implemented in the model, but a different approach was made to verify the results. With an efficiency of 40 %, the power needed to be produced by the generator, i.e. the load, is $\simeq 196kW$. Assuming that the generator is running at an optimal load of 80 % (CKPower n.d) would give a generator size of $\simeq 250kW$. From a fuel consumption chart by GeneratorSource n.d, we can read out that a 250kW size generator running at $\simeq \frac{3}{4}$ load will consume 13.6 gallons/hour, or 51.48 L/h. With the diesel generator running for about 250 seconds, and with an emission of 2.69 kgCO_2/L calculated from SSB 2017, the amount of CO_2 emitted from one lift was calculated to 9.63 kgCO_2. Taking into account the frequency of the winch, the CO_2 emitted for the traditional ROV was calculated to **1155.22 kg**CO_2, and **19.26 kg**CO_2 for the IKM RROV every 3 months.

The last calculation was done only to verify the results from table 5, as some assumptions had to be made in order to calculate the CO_2 emitted. A more thorough presentation of the calculations done is shown in appendix 5.

4.2.3 Assumptions

Several assumptions were made when calculating the emissions related to the use of the winch. Firstly, there will be drag forces acting on the ROV and TMS. For these forces to be taken into account, dimensions of the ROV+TMS and its drag coefficient would have to be known. It is assumed that the apparent weight of the ROV+TMS is slightly higher due to the unkown drag forces.
Secondly, the specifications of the gas turbine and diesel generator used to power the winch are also not known and the calculations are therefore done with general numbers found during research of available literature. For the diesel generator, another approach for calculating the emissions was made to verify that the results somewhat agreed.
Lastly, it is assumed that both the hoisting and lowering of the ROV require the same amount of power from the winch. In reality, lowering the ROV in water may require less power than lifting it and the calculated emission would be reduced by this. There could also be currents in the ocean affecting the power required to move the ROV under water, this is not accounted for in the calculations.

4.3 Onshore vs Offshore control room

For the offshore control room case, an operator works offshore on a specific rig. A 45 minute helicopter ride is needed to transport the employees from Florø to the rig. It was assumed that Bristow Norway, a company that specializes in transporting employees to offshore rigs, is used. Their fleet consists of 25 Sikorsky S-92 helicopters (*Bristow Norway* 2023). All data used here are taken from this helicopter model. All calculations performed hereinafter take into account that the employee travels back and forth from the rig. It is assumed that the employee uses the same transportation both ways, therefore the calculations are scaled by a factor of 2.

An average fuel burn was used to be able to calculate CO_2-emissions from one helicopter ride. The available literature show small discrepancies in fuel burn for the helicopter, with numbers ranging from 800-830L/h (Senzig and Cumper 2013). A fuel burn of 815L/h is used in the calculations. The helicopter uses standard JP-4 jet fuel that has a CO2-emission factor of 3.16kgCO2/kgFuel (IATA 2022), and a density of around 0.8kg/L (Exxonmobil 2022). It can carry up to 19 passengers. Equation (15) gives an estimate of the CO_2-emissions for this flight per passenger, assuming a 45 minute helicopter ride from Florø to the specific rig.

$$2 * 815\frac{L}{h} * \frac{45}{60}h * 3.16\frac{kgCO2}{kgFuel} * 0.8\frac{kgFuel}{L} * \frac{1}{19}\frac{1}{pax} = \mathbf{162.66}\frac{kgCO2}{pax} \tag{15}$$

Furthermore, emissions from transportation from some selected cities were made. The only direct route by plane to Florø is from Bergen, so first it was assumed that the employee is living in Bergen. Widerøe is the company that offers these flights and its duration is around 35 minutes. The type of aircraft used for this flight is from the De Havilland DHC-8 100 Series (Widerøe n.d), and it has an average fuel burn of around 550kg/h (Airlines-Inform n.d). As with the helicopter, this aircraft uses standard jet fuel with a CO2-emission factor of 3.16kgCO2/kgFuel (IATA 2022), and a density of around 0.8kg/L (Exxonmobil 2022). It can carry up to 39 passengers (BaeSystems n.d). Equation 17 gives an estimate of the CO_2-emissions for this flight per passenger, assuming a fully booked flight with 39 passengers.

$$2 * 550\frac{kgFuel}{h} * \frac{35}{60}h * 3.16\frac{kgCO2}{kgFuel} * \frac{1}{39}\frac{1}{pax} = \mathbf{52.00}\frac{kgCO2}{pax} \tag{16}$$

Secondly, it was assumed that the employee is living in Stavanger. A 40 minute flight is required to get from Stavanger to Bergen, and it is assumed that the employee flies with Widerøe. The type of aircraft used here is from the De Havilland DHC-8 400 Series (Widerøe n.d), with the same jet fuel described above. However, this aircraft has a fuel burn of 1.95kgFuel/km (Flyradius 2014) and carry a maximum of 78 passengers (BaeSystems n.d). It is assumed that the shortest possible route is chosen, i.e., a straight line between the two cities, which would yield a distance of 158 km (ICAO n.d) The emissions from flights back and forth between Stavanger and Bergen becomes:

$$2 * 1.95\frac{kgFuel}{km} * 158km * 3.16\frac{kgCO2}{kgFuel} * \frac{1}{78}\frac{1}{pax} = \mathbf{24.96}\frac{kgCO2}{pax} \tag{17}$$

Additional emissions can occur if the employee is situated in another city than Bergen and Stavanger, for example Oslo. Due to the large number of flights between Oslo and Bergen, it is assumed that the employee has chosen a flight with Norwegian. The type of aircraft for this flight is from the Boeing 737-800 Series, and the flight duration is 55 minutes. This aircraft burns an average of 3.59 kgFuel/km (Boeing 2006). It is assumed that the shortest possible route is chosen, i.e., a straight line between the two cities, which would yield a distance of 323 km (ICAO n.d). Assuming standard jet fuel and a fully booked flight with 189 passengers (Boeing 2024), the total emissions per passenger for this flight become:

$$2 * 3.59\frac{kgFuel}{km} * 323km * 3.16\frac{kgCO2}{kgFuel} * \frac{1}{189}\frac{1}{pax} = \mathbf{38.78}\frac{kgCO2}{pax} \tag{18}$$

A final consideration can be made on travel from residence in either Bergen, Stavanger or Oslo to the airport. In Bergen and Oslo, the employee can take the train to the airport. An average emission factor of 0.007kgCO2/km per passenger is used (Anneli Kamb 2022). In Stavanger, the employee would have to take the bus. Here, an average emission factor of 0.025kgCO2/km per passenger is used (Helle 2023). Furthermore, the approximate distances to the airport from Bergen's, Stavanger's and Oslo's city centers, respectively, have been calculated to be 20, 15 and 50 km. Equations 19, 20 and 21 give the emissions from Bergen, Stavanger and Oslo city centre to the airport, respectively. Equations 22, 23 and 24 estimate the emissions assuming that the employee drives to the airport.

$$2 * 20km * 0.007\frac{kgCO2}{km} = \mathbf{0.28kgCO2} \tag{19}$$

$$2 * 15km * 0.025\frac{kgCO2}{km} = \mathbf{0.75kgCO2} \tag{20}$$

$$2 * 50km * 0.007\frac{kgCO2}{km} = \mathbf{0.70kgCO2} \tag{21}$$

$$2 * 20km * 0.1082\frac{kgCO2}{km} = \mathbf{4.33kgCO2} \tag{22}$$

$$2 * 15km * 0.1082\frac{kgCO2}{km} = \mathbf{3.25kgCO2} \tag{23}$$

$$2 * 50km * 0.1082\frac{kgCO2}{km} = \mathbf{10.82kgCO2} \tag{24}$$

Additional emissions occur offshore due to the transportation of food and supplies to the rigs. Further it is assumed that one employee eats roughly 1.85kg of food each day (Ventures 2021). Additional supplies is neglected in this analysis because it might be time-dependent. It is important to note that in reality, this will increase the amount of emissions. An average emission factor of 0.016kgCO2/km per ton of goods is assumed for the shipping of food (Sinay 2023). A distance of 150 km from Florø to Visund/SnorreB is assumed. This is an estimate based of a general estimate of oil rigs locations from the norwegian coastline, and therefore it might be unprecise. Equation 25 gives the estimated emissions for transportation of food for a 2 week stay for one employee at an offshore rig:

$$1.85\frac{kg}{day} * 14days * 0.016\frac{kgCO2}{ton * km} * \frac{1}{1000}\frac{ton}{kg} * 150km = \mathbf{0.062kgCO2} \tag{25}$$

Other than transportation-related emissions, an assessment of the electricity consumption and transport of food has also been conducted. Off-shore rigs are mainly self-sufficient on electricity production, and further it is assumed that gas turbines are utilized. In order to estimate emissions regarding electricity consumption, the average electricity use per person in Norway had to be estimated. To do so, data from SSB has been utilized. According to SSB, a total of 42700kWh of electricity was used in households in 2023 (SSB 2023a). In addition to this, there was 2581721 households in Norway with an average of 2.11 people per household (SSB 2023b). Equation 26 uses this data to find an average electricity consumption per person in Norway. Further, assuming an average emission factor of 0.21kgCO2/kWh (Svendsen et al. 2022), Equation 27 gives the estimated CO2-emissions from electricity consumption for a 2 week stay at a a offshore rig.

$$42700 * 10^6 \frac{kWh}{year} * \frac{1}{2581721} * \frac{1}{2.11 pax} = \mathbf{7838.56} \frac{kWh}{pax * year} \tag{26}$$

$$0.21 \frac{kgCO2}{kWh} * 7838.56 \frac{kWh}{pax * year} * \frac{2}{52} year = \mathbf{63.31} \frac{kgCO2}{pax} \tag{27}$$

Next, the onshore control room case was analyzed. In this case, the employee works onshore in a control room in Bryne. The employee lives in a different city than Bryne, and it is assumed to be Bergen, Stavanger or Oslo.

Living in Oslo or Bergen, it is assumed that the employee flies from Oslo/Bergen to Sola airport in Stavanger and then takes the train from Stavanger to Bryne. Equation 17 estimates the total emissions for the back-and-forth flights between Bergen and Stavanger. In addition to this, a flight distance of 340 km from Oslo to Stavanger is assumed (ICAO n.d). It is assumed that the employee has chosen a flight with Norwegian. As previously described, the type of aircraft for this flight is from the Boeing 737-800 Series, with an average fuel burn of 3.59 kgFuel/km (Boeing 2006). Assuming a fully booked aircraft of 189 passengers, the total emissions for flights back and forth between Oslo and Stavanger becomes:

$$2 * 3.59 \frac{kgCO2}{km} * 340 km * 3.16 \frac{kgCO_2}{kgFuel} * \frac{1}{189} \frac{1}{pax} = \mathbf{40.8} \frac{kgCO2}{pax} \tag{28}$$

Finally, emission from car ride and train ride from Stavanger to Bryne has been evaluated. An approximate distance of 31 km and an average emission factor of 0.1082 kgCO2/km for car and 0.007kgCO2/km for train has been used (EEA 2023, Anneli Kamb 2022). Equation 29 and 30 shows the result.

$$2 * 31 km * 0.1082 \frac{kgCO2}{km} = \mathbf{6.71kgCO2} \tag{29}$$

$$2 * 31 km * 0.007 \frac{kgCO2}{km} = \mathbf{0.434kgCO2} \tag{30}$$

Looking at the onshore electricity production, an average emission factor of 0.011kgCO2/kWh has been assumed (NVE 2021). With an electricity consumption as calculated in Equation 26, the estimated onshore emissions related to electricity consumption becomes:

$$0.011 \frac{kgCO2}{kWh} * 7838.56 \frac{kWh}{year * pax} * \frac{2}{52} = \mathbf{3.32} \frac{kgCO2}{pax} \tag{31}$$

Table 6 and Table 8 lists the total emissions for transport back and forth from residence to offshore and onshore control room, respectively.

Table 6: Transport emissions to Offshore control room based on residence city and transportation methods. Values calculated as roundtrip, apply for every tour (14 days)

Residence	**Description**	**Emissions [kgCO$_2$/tour]**
Bergen	Train to Flesland, flight to Florø, helicopter ride to rig	**214.94**
Stavanger	Bus to Sola, flight to Bergen, flight to Florø, helicopter ride to rig	**240.37**
Oslo	Train to Gardermoen, flight to Bergen, flight to Florø, helicopter ride to rig	**254.14**
Bergen	Car to Flesland, flight to Florø, helicopter ride to rig	**218.99**
Stavanger	Car to Sola, flight to Bergen, flight to Florø, helicopter ride to rig	**244.87**
Oslo	Car to Gardermoen, flight to Bergen, flight to Florø, helicopter ride to rig	**264.20**

Table 7: Transport emissions to Onshore control room based on residence city and transportation methods. Values calculated as roundtrip, apply for every tour (14 days)

Residence	**Description**	**Emission [kgCO$_2$/tour]**
Bergen	Flight to Sola, bus to Stavanger, train to Bryne	**25.56**
Stavanger	Car to Bryne	**6.71**
Oslo	Flight to Sola, bus to Stavanger, train to Bryne	**42.0**

Table 8: Emission from energy consumption and food transportation

Control room	**Description**	**Emission [kgCO$_2$/tour]**
Offshore	Energy from Self-supplied by gas turbines	**63.31**
Onshore	Energy from Norwegian energy mix	**3.32**
Offshore	Food transport to rig	**0.062**

5 Conclusions and Takeaways

For case 1 - Elecric vs Hydraulic ROV the results speake quite clearly that the electric ROV is the less emission intensive of the two ROV for all approaches and in both operational modes. This is in large due to higher efficiency of the electric thruster system, as well as avoiding the idle power consumption which is present for a hydraulic ROV. The results for this case does only represent relative values, further and deeper examination of the emission for both ROV's needs to be made in order to achieve sound absolute emission estimates.

For case 2 - The emission when using IKM RROV i vastly lower compared to using the traditional WROV. There was observed some substantial differences in whether the winch was power by gas turbines on rig or from support vessels, where power from rig there was almost three times less emissions observed. Due to the way larger frequency of hoists for the traditional ROV its emissions were way higher compared to the IKM ROV. The main uncertainties for this case is in regards to drag forces not being included and the assumption that the winch uses equal amount of power when lowering and raising the ROV's.

For case 3 - onshore vs offshore control room the onshore control room is the preferred alternative of the two, seen from an emission perspective. Due to the larger requirements for transportation in the case for offshore control room, way higher emission are observed in this case. The same can be observed when examining the emission for food and energy consumption, where generally the emission for sustaining crew offshore is way higher than onshore.

Bibliography

Airlines-Inform (n.d). 'Bombardier Dash 8-100/200'. In: URL: https://www.airlines-inform.com/commercial-aircraft/dash-8q200.html.

Anneli Kamb, Jörgen Larsson og (2022). 'Metodrapport för www.klimatsmartsemester.se'. In: URL: https://klimatsmartsemester.se/sites/default/files/metodrapport-klimatsmart-semester-version3.pdf.

BaeSystems (n.d). 'De Havilland Canada DHC-8 Dash 8'. In: URL: https://www.baesystems.com/en/heritage/de-havilland-canada-dhc-8-dash-8.

Boeing (2006). 'Fuel economy in aircraft'. In: URL: https://web.archive.org/web/20140725005129/http://www.boeing.com/assets/pdf/commercial/startup/pdf/737ng_perf.pdf.

— (2024). 'Boeing 737 Next Generation'. In: URL: https://www.boeing.com/commercial/737ng#Technical%20Specs.

Boyce, M. P (2006). 'An Overview of Gas Turbines'. In: URL: http://www.sciencedirect.com/science/article/pii/B9780750678469500043.

Bristow Norway (29th Sept. 2023). In: *Wikipedia*. Page Version ID: 23859257. URL: https://no.wikipedia.org/w/index.php?title=Bristow_Norway&oldid=23859257 (visited on 23rd Feb. 2024).

CKPower (n.d). 'KEYS TO RUNNING YOUR GENERATOR EFFICIENTLY'. In: URL: https://ckpower.com/keys-to-running-your-generator-efficiently/.

EEA (2023). 'Average emissions from new cars and vans in Europe continue to fall, according to provisional data'. In: URL: https://www.eea.europa.eu/en/newsroom/news/average-emissions-from-new-cars-and-vans.

Energy, US Department of (n.d). 'DETERMINING ELECTRIC MOTOR LOAD AND EFFICIENCY'. In: URL: https://www.energy.gov/eere/amo/articles/determining-electric-motor-load-and-efficiency.

Energy Efficiency, Copenhagen Center on (n.d). 'Improving ship efficiency'. In: URL: https://c2e2.unepccc.org/kms_object/improving-ship-efficiency/.

Exxonmobil (2022). 'Jet fuel'. In: URL: https://www.exxonmobil.com/en-bd/commercial-fuel/pds/gl-xx-jetfuel-series.

Flyradius (2014). 'Bombardier Q400 Fuel Burn - Consumption'. In: URL: https://www.flyradius.com/bombardier-q400/fuel-burn-consumption.

Fossil Energy, Office of and Carbon Management (n.d). 'How Gas Turbine Power Plants Work'. In: URL: https://www.energy.gov/fecm/how-gas-turbine-power-plants-work#:~:text=A%20simple%20cycle%20gas%20turbine,of%2060%20percent%20or%20more..

GeneratorSource (n.d). 'Approximate Diesel Fuel Consumption Chart'. In: URL: https://www.generatorsource.com/Diesel_Fuel_Consumption.aspx.

Helle, Knut-Erik (2023). 'Klimagassutslippet fra ulike reisemåter'. In: URL: https://www.framtiden.no/tips/klimagassutslippet-fra-ulike-reisemaater.

IATA (2022). 'IATA Carbon Offset Program - Frequently Asked Questions'. In: URL: https://www.iata.org/contentassets/922ebc4cbcd24c4d9fd55933e7070947/icop_faq_general-for-airline-participants.pdf.

ICAO (n.d). 'ICAO Carbon Emissions Calculator (ICEC)'. In: URL: https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx.

Ipieca (2022). 'Open-cycle gas turbines (2022)'. In: URL: https://www.ipieca.org/resources/energy-efficiency-database/open-cycle-gas-turbines-2022.

Jamborowicz, Marek (2020). ‘Factors that impact thruster efficiency’. In: URL: https://blog.sleipnergroup.com/en/factors-that-impact-thruster-efficiency.

Nagal, Lauren (2023). ‘What is the Average Efficiency of an Electric Motor’. In: URL: https://www.tytorobotics.com/blogs/articles/what-is-the-average-efficiency-of-an-electric-motor.

NVE (2021). ‘Lavt klimagassutslipp knyttet til norsk strømforbruk i 2021’. In: URL: https://www.nve.no/nytt-fra-nve/nyheter-energi/lavt-klimagassutslipp-knyttet-til-norsk-stroemforbruk-i-2021/.

Petroleum, Norwegian (n.d). ‘CONVERSION’. In: URL: https://www.norskpetroleum.no/en/calculator/about-energy-calculator/.

Power, General (n.d). ‘Diesel Generator vs. Gas Generator: Which is More Efficient?’ In: URL: https://www.genpowerusa.com/blog/diesel-generator-vs-gas-generator-which-is-more-efficient/#:~:text=Typically%20a%20diesel%20generator%20will,units%20are%20delivered%20as%20output.

Senzig, David and Jordan Cumper (1st July 2013). *Fuel consumption of ADS-B and non-ADS-B helicopter operations in the Gulf of Mexico*. DOI: 10.13140/RG.2.2.19994.64969.

Ships, Sustainable (n.d). ‘Specific Fuel Consumption [g/kWh] for Marine Engines’. In: URL: https://www.sustainable-ships.org/stories/2022/sfc#:~:text=Specific%20Fuel%20Consumption%20(SFC)%20of,stroke%20or%20four%2Dstroke)..

Sinay (2023). ‘How much does the shipping industry contribute to global CO2 emissions?’ In: URL: https://sinay.ai/en/how-much-does-the-shipping-industry-contribute-to-global-co2-emissions/.

SSB (2017). ‘Emission factors used in the estimations of emissions from combustion’. In: URL: https://www.ssb.no/_attachment/291696/.

— (2023a). ‘Elektrisitet’. In: URL: https://www.ssb.no/statbank/table/14091.

— (2023b). ‘Familier og husholdninger’. In: URL: https://www.ssb.no/befolkning/barn-familier-og-husholdninger/statistikk/familier-og-husholdninger.

Svendsen, H. G et al. (2022). ‘The Low Emission Oil and Gas Open reference platform—An off-grid energy system for renewable integration studies’. In: URL: https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/3036625/Svendsen2022tle_VoR.pdf?sequence=1.

Ventures, Good Seed (2021). ‘Learn more about sustainable food systems’. In: URL: https://goodseedventures.com/worldwide-food-consumption-per-capita-2/.

Volker-Quasching (2022). ‘Specific Carbon Dioxide Emissions of Various Fuels’. In: URL: https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php.

Widerøe (n.d). ‘Widerøes flytyper’. In: URL: https://www.wideroe.no/om-selskapet/flytyper.

A Calculations for "Use of traditional vs IKM ROV"

With a operation depth of 500m and the winch lifting at a speed of 2m/s, the time the winch is in use is:

$$\frac{500m}{2m/s} = 250s = 4.17m = 0.0694h \tag{32}$$

The effective weight of the ROV in water is calculated by subtracting the buoyant force, with V_{ROV} being the volume of the ROV (2.5m/1.5m/1.5m), ρ_{water} being the density of saltwater, and g being the gravitational constant.

$$Weight_{effective} = 4t(weightofTMS) = 39226.6N \tag{33}$$

The power required to move the ROV is the effective weight in newtons, or force, times the displacement divided by duration of the lift.

$$P_{winch} = \frac{Fs}{t} = \frac{39226.6N * 500m}{250s} = 78.45kW \tag{34}$$

A.1 Gas turbine calculations

With an efficiency of 30%, the power outputted by the turbine is:

$$P_{turbine} = \frac{P_{winch}}{eff_{turbine}} = \frac{78.45kW}{30\%} = 261.6kW \tag{35}$$

The energy used by the winch during the lift becomes:

$$E_{turbine} = P_{turbine} * t = 261.6kW * 0.069h = 18.15kWh \tag{36}$$

Using the gas turbine emission from Svendsen et al. 2022 and SSB 2017, and with the conversion of Sm^3 to kWh form Petroleum n.d, the emission factor for one lift using the gas turbine becomes:

$$2.34\frac{kgCO_2}{Sm^3} * 18.15kWh = 0.212\frac{kgCO_2}{kWh} * 18.15kWh = 3.85kgCO_2 \tag{37}$$

For the traditional ROV the winch is used 5 times a week, for 4 weeks, for 3 months, up and down. For the IKM ROV the winch is only in use once per 3 months, up and down.

$$5 * 4 * 3 * 2 * 3.91kgCO_2 = 462kgCO_2 \tag{38}$$

$$2 * 1.177kgCO_2 = 7.7kgCO_2 \tag{39}$$

A.2 Diesel generator calculations

For the diesel generator, using an efficiency rating of 40% the power outputted by the generator is:

$$P_{generator} = \frac{P_{winch}}{eff_{generator}} = \frac{78.45kW}{40\%} = 196.125kW \tag{40}$$

With the time the winch is in use, the energy used becomes:

$$E_{generator} = P_{generator} * t = 196.125kW * 0.069h = 13.61kWh \tag{41}$$

With the fuel consumption from Ships n.d and the emission factor from SSB 2017, the emissions from one lift with the diesel generator becomes:

$$225\frac{g_{diesel}}{kWh} * 13.61kWh * 3.17\frac{gCO_2}{g_diesel} = 9.7kgCO_2 \tag{42}$$

For the traditional ROV the winch is used 5 times a week, for 4 weeks, for 3 months, up and down. For the IKM ROV the winch is only in use once per 3 months, up and down.

$$5 * 4 * 3 * 2 * 9.86 kgCO_2 = 1166 kgCO_2 \tag{43}$$

$$2 * 9.86 kgCO_2 = 19.43 kgCO_2 \tag{44}$$

A Calculations for Onshore vs Offshore Control Room

Helicopter emissions from Florø to Offshore rig (Visund B/Snorre):

$$2 * 815 \frac{L}{h} * \frac{45}{60} h * 3.16 \frac{kgCO2}{kgFuel} * 0.8 \frac{kgFuel}{L} * \frac{1}{19} \frac{1}{pax} = \mathbf{162.66} \frac{kgCO2}{pax} \tag{45}$$

Flight emissions from Bergen to Florø:

$$2 * 550 \frac{kgFuel}{h} * \frac{35}{60} h * 3.16 \frac{kgCO2}{kgFuel} * \frac{1}{39} \frac{1}{pax} = \mathbf{52.00} \frac{kgCO2}{pax} \tag{46}$$

Flight emissions from Oslo to Bergen:

$$2 * 3.59 \frac{kgFuel}{km} * 323 km * 3.16 \frac{kgCO2}{kgFuel} * \frac{1}{189} \frac{1}{pax} = \mathbf{38.78} \frac{kgCO2}{pax} \tag{47}$$

Train emissions from Oslo city centre to Gardermoen airport:

$$2 * 20 km * 0.007 \frac{kgCO2}{km} = \mathbf{0.28kgCO2} \tag{48}$$

Train emissions from Bergen city centre to Flesland airport:

$$2 * 50 km * 0.007 \frac{kgCO2}{km} = \mathbf{0.70kgCO2} \tag{49}$$

Total emissions from ferry transport when driving from Bergen to Bryne:

$$2 * 0.226 \frac{kgCO2}{km} * 30.5 km * \frac{1}{545} \frac{1}{pax} = \mathbf{0.026} \frac{kgCO2}{pax} \tag{50}$$

Total emissions from car ride between Bergen and Bryne:

$$2 * 0.1082 \frac{kgCO2}{km} * 205.5 km = \mathbf{44.48} kgCO2 \tag{51}$$

Total emissions from car ride between Oslo and Bryne:

$$2 * 0.1082 \frac{kgCO2}{km} * 533 km = \mathbf{115.34} kgCO2 \tag{52}$$