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Estimating greenhouse gas emissions from ships on four ports of Georgia from 2010 to 2018

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Abstract This study is a comprehensive inventory of the greenhouse gas emissions from ships in the Georgian ports and aims to analyse the level of exhaust gas emissions in ports. Georgia has four main ports (the Poti Sea Port, the Batumi Port, the Port of Kulevi, and the Port of Supsa) which are a vital link in Georgia's economy and transfer point for handling oil and oil products. The ship activity-based method is used to calculate the emissions of NO_X, CO_2, VOC, PM, and SO_2 from ships between 2010 to 2018 years. The analysis is executed according to the type of ships (container, bulk dry, general cargo, tanker, chemical, liquified gas, and others) and operational modes (cruising, manoeuvring, and hoteling). The total emissions from ports are 54.640, 44.030, 11.910, and 9.206 tonnes per year for Batumi, Poti, Kulevi, and Supsa, respectively. The study indicates that the Batumi Port is the main source of atmospheric pollution in the region followed by the Poti Sea Port. Tanker, general cargo, and container ships are the main polluters at all ports and emit almost 82% of all emissions in the Georgian ports. The greenhouse gas emissions emitted from vessels during the mode of cruising were 82% of the total amount; manoeuvring emissions were 5% and hoteling 13% in operational modes. The environmental costs of ports can reach to €19.1 million or €14.288 per ship call in 2018. The uncertainties of the pollutant emission estimates were measured, with lower bounds of − 12.3 to − 33.9% and upper bound of 10.8 to 30.0% at 95% confidence intervals. The lower uncertainties in the study emphasised the importance of the ship activity-based method in improving ship emission estimates.

Keywords Emissions inventory · Ship emissions · Environmental cost · Environmental pollution · Air pollutants · Environmental assessment

Highlights
- A comprehensive inventory of the shipping emissions in the Georgian ports was created.
- Emissions of NO_X, CO_2, VOC, PM, and SO_2 from ships during cruising, manoeuvring, and hoteling were estimated from 2010 to 2018.
- Emissions for the 4 major ports in Georgia were presented.
- No previous study has examined the port emissions from shipping in the study area.

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Introduction

International maritime trade increased its capacity by 2.6% in 2019, and its capacity is anticipated to increase with an average growth rate of 3.5% between 2019 and 2024 which accounts for 90% of world trade (UNCTAD, 2019). As the need for energy and raw materials continues to increase in the globalised world, maritime trade remains important. Maritime trade is accountable for 3.3% of worldwide CO_2 emissions, although it is the greenest mode of transport compared to other modes of transport and emits the lowest carbon dioxide emissions per unit load per kilometre (Buhaug et al., 2009). CO_2, NO_X, and SO_X emissions from exhaust gas emissions from ships by fuel consumption account for about 2.2%, 15%, and 5–8% of international anthropogenic emissions (IMO, 2016; Tzannatos, 2010; Song, 2014). This ratio is not too low to underestimate. It was observed that 70% of the ship's movements take place at 200 nm from land, 44% at 50 nm, and 36% at 25 nm (Buhaug et al., 2009). Twenty-five percent of the world merchant fleet is navigating close to the coastline, 80% of them are in the position of an anchor at the port/hoteling mode, and 55% of them are in the port areas (ICCT, 2007) This means that generally, ships navigate close to port areas and NO_X, SO_X, and PM emissions from the ships will have dangerous effects on people health, ecosystem, and environment (Bayirhan et al., 2019; Corbett et al., 2007; Qinbin et al., 2002; Tokuslu et al., 2020). The effects of these emissions are manifested as asthma, breathing diseases, heart attacks, cardiovascular disease, premature mortality, and lung cancer (NRDC, 2004).

In recent years, there has been a growing amount of literature on estimating global (Corbett et al., 2007; Cooper & Gustaffson, 2004; Corbett & Köhler, 2003; Dalsøren et al., 2007; Entec, 2007) and regional shipping emissions. All these studies emphasised the importance of ship emissions and revealed the effects of emissions on the environment. For the regional studies, Alver et al. (2018) investigated the emissions from shipping in the Samsun Port in Turkey, and Nunes et al. (2017) assessed the shipping emissions (NO_X, N_2O, $PM_{2.5}$, PM_{10}, NMVOC, CO_2, CH_4, CO, HC, and SO_2) on four main ports (Sines, Viana do Castelo, Setúbal, and Leixoes) of Portugal through the activity-based methodology. Styhre et al. (2017) examined the greenhouse gas (GHG) emissions from ships from Port of Long Beach, Port of Osaka, Port of Gothenburg, and Sydney Ports. Tichavska and Tovar (2015) estimated the air pollutants originated from cruise and ferry operations in Las Palmas Port with using the Automatic Identification System (AIS) messages. Chen et al. (2016) developed a detailed exhaust emission inventory of ships for Tianjin Port by using AIS data. Emissions (SO_2, $PM_{2.5}$, and NO_X) from cruise ships in the Greek ports such as Piraeus, Santorini, Mykonos, Corfu, and Katakolo were calculated by Maragkogianni and Papaefthimiou (2015).

Together these studies provide important insights into the emissions from ships whilst in ports and highlight the need for analysing other ports to present their effects on people health, the environment, and the ecosystem. Emissions from ships are part of the port emissions. No previous study has examined the emissions from shipping in this region. The main purpose of this study was to calculate NO_X, CO_2, SO_2, VOC, and PM emissions during cruising, manoeuvring, and hoteling operations in ports of Georgia using a bottom-up approach based on the ship activities from 2010 to 2018. This study will fill the gap in the existing literature by assessing emissions from shipping on the east side of the Black Sea and will create a shipping emission inventory for the region.

Materials and methods

Study location and ports characteristics

Georgia is situated on the eastern Black Sea shoreline and a sea hub with Black Sea ports of Turkey, Ukraine, Russia, Romania, and Bulgaria and connects the Caucasus region and Central Asia with international sea trade. Georgia has four main ports which are the Poti Sea Port, the Batumi Port, the Port of Kulevi, and the Port of Supsa, and Fig. 1 presents us the location of these ports (APMT, 2019). All the ports are a vital link in the Georgia economy and transfer point for handling oil and oil products. Also, the ports serve as an international gateway with connection to all main cities through Georgia to the Caucasus region and Central Asia countries. The ports are the closest destination to reach to these countries.

The Poti Sea Port

The Poti Sea Port is managed by APM Terminals which is the biggest commercial port of Georgia with 10 million tons capacity. Port is a vital access point and gateway for the Caucasus Region and Central Asia and operating 365 days a year with its 15 berths. Port is the largest container terminal in the region and responsible for handling liquid bulk, dry bulk, and passenger ferries (APMT, 2019).

The Batumi Port

The Batumi Port is located at the centre of the Adjara Autonomous Republic of Georgia which is one of the resort places of the Black Sea. Port is managed

Fig. 1 The location of the studied ports (APMT, 2019)

by Kazakhstan's national oil and gas company. Port has five terminals (oil, container, the railway ferry, dry cargo, and passenger) and 11 berths that serve manoeuvre of different types of cargo. Port handles 18 million tons of goods per year. The port hosts approximately 700 ships per year such as solid bulk, passenger, container, general cargo, and tanker ships (BP, 2019).

The Port of Kulevi

The Port of Kulevi is a small river port which handles crude, petroleum products, and LPG. Port is managed by Black Sea Terminal Ltd., a subordinate company of the State Oil Company of Azerbaijan (SOCAR). The port with its three piers moves about 10 million tons of oil cargo (black oil, fuel oil, and other oil products) per year which is delivered from Azerbaijan, Turkmenistan, and Kazakhstan, after extraction from the Caspian Sea and Black Sea fields (KP, 2019).

The Port of Supsa

The Port of Supsa is a modern oil terminal handling vessel of 150.000 dwt with an off-shore mooring and managed by Azerbaijan Oil Consortium. The port is located at the junction of the Western Route Export Pipeline route transporting crude oil from the Caspian Sea. It handles crude oil and petroleum with its 8 million tons capacity per year. The port has a substantial role in the Georgian and Azerbaijan economy (SP, 2019).

Ship movements

The number of ship visits made at each port between 2010 and 2018 years is shown in Fig. 2 (APMT, 2019; BP, 2019; KP, 2019; SP, 2019) and the number of ships visiting the Poti Sea Port and the Batumi Port was substantially greater than the other two ports. The Poti Sea Port and the Batumi Port have the capacity for handling every type of ship in Georgian coasts. The total number of ships visiting the Poti Sea Port was the maximum (932 ship) in 2010, 862 ship calls for the Batumi Port in 2011, 217 ship calls for the Port of Kulevi in 2015, and 104 ship calls for the Port of Supsa in 2014, respectively. From Fig. 2, it can be concluded that the number of ships tends to decrease, and the tonnage and height of the ships increase. In the Batumi Port, whilst container cargo throughput in 2017 was 76.025 TEU, it increased to 90.002 TEU in 2018. Also, dry cargo capacity was 795 thousand MT in 2017; it

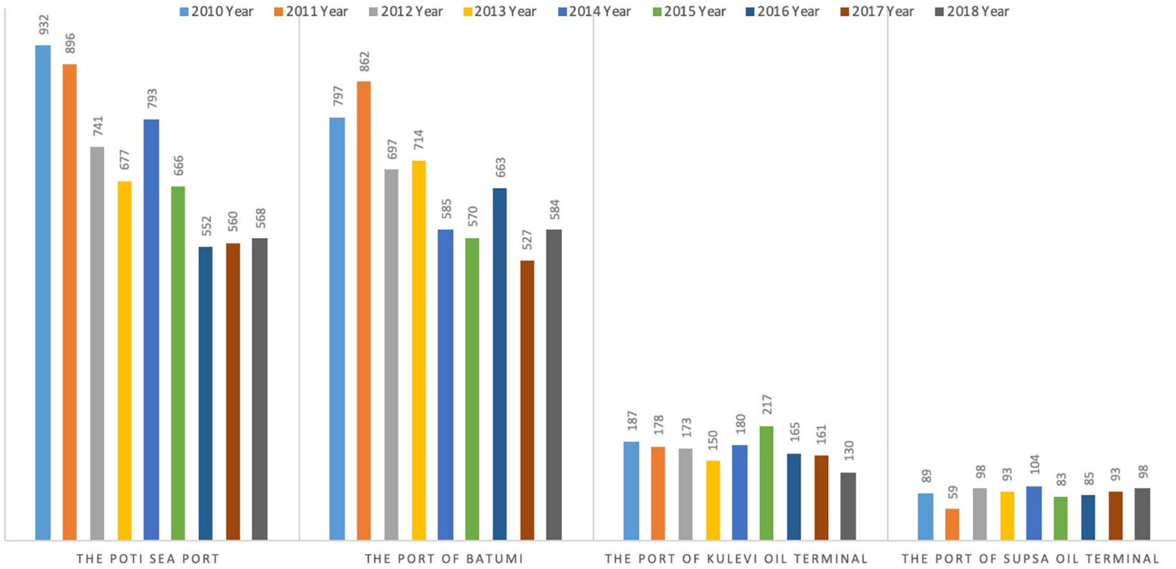

Fig. 2 The number of ship visits at each port (APMT, 2019; BP, 2019; KP, 2019; SP, 2019)

reached 1.189 thousand MT in 2018 (BP, 2019). The same increase is also available in other ports and this is expected to be a result of being at the intersection line of the energy project (Baku-Tbilisi-Ceyhan pipeline) and the ancient silk road (Baku-Tbilisi-Kars). These changes reflected in the results of the analysis.

The ship calls for the Port of Kulevi are 187, 178, 173, 150, 180, 217, 165, 161, and 130, which is an average of 171 per year. Years 2013, 2015, and 2018 are not so close to the average. Year 2013 (150 ship calls) is − 14% from average, 2015 (217 ship calls) is + 27% from average, whilst 2018 (130 ship calls) is − 24% from average. Also, if we see the lowest year (130) and the highest (217), there is a significant difference of about 67% between them. The ship calls for the Port of Supsa are 89, 59, 98, 93, 104, 83, 85, 93, and 98 which is an average of 89 per year. Years 2011 and 2014 are not so close to the average. Year 2011 (59 ship calls) is − 51% from average, whilst 2014 (104 ship calls) is + 14% from average.

The types of ships making the port visit at each port during 2010 and 2018 are shown in Fig. 3. The four ports have different characteristics. The Poti Sea Port has a very large share of container and general cargo ships whilst the Batumi Port is hosting tanker ships and general cargo. The Port of Kulevi and the Port of Supsa are home to a significant number of tanker ships. Generally, seven types of ships visited the Georgian ports such as liquefied gas, tanker, chemical, bulk dry, container, ro-ro cargo, and general cargo. The percentage ratio between the number of ship calls and ship types for the studied ports is shown in Table 1.

Data collection and engine powers

For calculation, the ship activity-based method was used and the required data such as the type of ship, arrival and departure data of ships, cruising, times during manoeuvring and hoteling, and tonnage values of ships were collected from the harbour authorities for each ship. The period covered all the ship movements in ports for the studied years. The data of four ports were involved in the study. Port calling data did not contain the power of the main and auxiliary engine of ships. As it was difficult to find the actual engine details and the speed of the ships, the power of the main and auxiliary engine and cruising speeds of the ships were accepted as shown in Table 2 (Lavender et al., 2006). Eight main ship categories were considered in this study: (i) chemical, (ii) tanker, (iii) liquefied gas, (iv) bulk dry, (v) general cargo, (vi) container, (vii) ro-ro cargo, and (viii) others. Each type of ship stated by harbour authorities were divided into the eight main categories described above, according to the Entec (2005, 2010) study. Livestock carrier, naval ships, fishing boats, supply ships, tugboats,

Fig. 3 The types of ships making port visit at each port during 2010 and 2018: (**a**) the Poti Sea Port, (**b**) the Port of Batumi, (**c**) the Port of Kulevi, and (**d**) the Port of Supsa

hopper-dredgers, and unbeknown ships were noted in the "others" category.

Load factors and operational modes

The main and auxiliary engine load factors were learned from the port pilot captain, who helped the ships approach the Poti Sea Port, and these load factors were stated to be the same for ships arriving at the other ports (Batumi, Kulevi, Supsa) in Georgia. The main and auxiliary engine load factors were obtained for the operational modes of each visiting ship (cruising, manoeuvring, hoteling), and these values were adopted as 80% for LF_{ME}, 30% for LF_{AE} in cruising mode, 20% for LF_{ME}, 50% for LF_{AE} in manoeuvring mode, 20% for LF_{ME}, 40% for LF_{AE} in hoteling mode (except tankers), 20% for LF_{ME}, and 60% for LF_{AE} in hoteling mode (for tankers) (Entec, 2005, 2010). Total cruising distance for calculation was 20 nm from the Georgian coastline since this distance was the low-speed zone and the pilotage, and it was determined according to navigational routes by using the navigational charts of Georgia. Every ship had to navigate this distance to enter the ports. Times during manoeuvring and hoteling were calculated in hours and obtained from the harbour authorities. The average time for manoeuvring for all types of visiting ships was 1 h which implied a total time of ship advent and exit. Hoteling durations were obtained from the harbour authorities as it was 38 h for liquefied gas, chemical, and tanker ships; 52 h for bulk dry; 14 h for container; 15 h for ro-ro cargo; 39 h for general cargo; and 27 h for other ships, respectively.

Emission estimation methodology

Important advancement has been made in the calculation of port emissions in different regions of the world. To date, various approaches have been developed and introduced to calculate ship emissions. In the literature, two approaches are generally used in the calculation of ship emissions. The first is the calculation made according to the amount of fuel used which is called top-down, and the second is the calculation made according to the movements and operations made by the ship which is called bottom-up.

Table 1 The percentage ratio between the number of ship calls and ship types for the studied ports

Georgian ports	Study year	Ship calls	Container (%)	General cargo (%)	Tanker (%)	Bulk dry (%)	Ro-ro cargo (%)	Chemical (%)	Liquefied gas (%)	Other ships (%)
The Poti Sea Port	2018	568	44	39	5	6	4	1	0	1
The Batumi Port		584	9	25	44	5	0	7	0	10
The Port of Kulevi		130	0	0	65	0	0	22	13	0
The Port of Supsa		98	0	0	100	0	0	0	0	0

Table 2 Powers of main and auxiliary engine of ships and cruising speeds (Lavender et al., 2006)

Ship type	Speed factor (knots)	Estimated main engine power kW (total power of all engines)						Estimated auxiliary engine power kW (medium speed)					
		< 500 GRT	500–999 GRT	1000–4999 GRT	5000–9999 GRT	10,000–49,999 GRT	≥ 50,000 GRT	< 500 GRT	500–999 GRT	1000–4999 GRT	5000–9999 GRT	10,000–49,999 GRT	≥ 50,000 GRT
Liquified gas	16	650	700	2250	5350	11,600	15,200	75	100	125	300	400	1000
Chemical	15	1000	-	2000	5000	10,250	-	40	50	165	300	435	-
Tanker	14	600	950	2200	4300	9600	17,200	40	50	165	300	435	530
Bulk dry	14	550	750	2700	5000	8800	17,000	20	40	175	300	380	500
General cargo	14	550	950	1800	5500	8500	-	20	40	175	300	380	-
Container	20	1000	1750	2950	6000	17,200	35,000	40	60	160	500	1400	1400
Ro-ro cargo	18	1500	1900	4300	7200	11,600	12,550	100	150	350	1000	2500	4000
Other ships	15	900	1200	2400	6200	9900	18,700	50	80	200	450	900	1750

Several shipping emission inventory studies have been created by using these approaches.

In a top-down approach, emissions are calculated by multiplying the fuel consumed by ships to produce energy by emission factors based on the fuel type. Fuel consumption generally depends on the installed engine power for a ship, cruising time, the fuel consumed per power unit (kW), and the default average engine load. Worldwide maritime emissions are generally calculated using the top-down approach (Corbett & Köhler, 2003; Endresen et al., 2003; Eyring et al., 2005).

The bottom-up approach is giving more precise and large-scale results in estimating emissions according to data such as engine power, load factor, ship speed, and times during operational (cruising, manoeuvring, and hoteling) modes. Bottom-up approaches are limited to smaller-scale or regional emission inventories, and most port emissions studies with high ship traffic have been calculated by the bottom-up approach (Berechman & Tseng, 2010; Deniz & Kilic, 2009; Fan et al., 2016; Fu et al., 2012; Liu et al., 2014; Ng et al., 2013; Nunes et al., 2017; Song & Shon, 2014; Tokuslu & Burak, 2021; Tzannatos, 2010; Yau et al., 2012). The Samsun Port and the Constanta Port which are the largest ports in the Black Sea region were analysed by Alver et al. (2018) and Popa and Florin (2014). Other ports located on the Black Sea coasts did not get similar attention and were not investigated because of lack of emission inventory which was a great obstacle for calculation. Consequently, a comprehensive shipping emission inventory needed to be created for the ports of Georgia which constituted of 10% of the Black Sea coast to fill the gap.

This research contained an inventory of greenhouse gas (GHG) emissions from the ships on the four ports of Georgia (the Poti Sea Port, the Batumi Port, the Port of Kulevi, and the Port of Supsa). In this study, Entec Uk Limited Methodology (Entec, 2005) was preferred, which was one of the bottom-up approaches based on data we had. Entec Uk Limited Methodology was created by the European Commission Directorate-General Environment Agency in 2005 to constitute emission inventory with emission factors covering cruising, manoeuvring, and hoteling operation modes for each type of ships in European Seas. This methodology is an activity-based method and commonly used for shipping and port emissions in literature. For this methodology, we collected the data of the type of ship, ship gross tonnage, ship speed, and manoeuvring/hoteling times from port authorities. Entec Uk Limited Methodology emission formula is shown as follows:

$$E_{cruising} = D * \left[\left[\mathbf{ME} * \mathbf{LF_{ME}} \right] + \left[\mathbf{AE} * \mathbf{LF_{AE}} \right] \right] * \mathbf{EF_{cruising}} / \mathbf{V} \tag{1}$$

$$E_{\mathbf{manoeuvering}} = T * \left[\left[\mathbf{ME} * \mathbf{LF_{ME}} \right] + \left[\mathbf{AE} * \mathbf{LF_{AE}} \right] \right] * \mathbf{EF_{manoeuvering}} \tag{2}$$

$$E_{\mathbf{hoteling}} = T * \mathbf{AE} * \mathbf{LF_{AE}} * \mathbf{EF_{hoteling}} \tag{3}$$

$E_{cruising}$, $E_{manoeuvring}$, and $E_{hoteling}$ are the emissions of pollutants (NO_X, CO_2, VOC, PM, and SO_2) during cruising, manoeuvring, and hoteling modes (units: tonne); D is the distance a ship navigates (units: mile); ME is the power of main engine (units: kW); LF_{ME} is the main engine load factor (units: %); AE is the power of auxiliary engine (units: kW); LF_{AE} is the auxiliary engine load factor (units: %); V is the speed of ship (units: knot/h); and T is the time consumed at operational mode of manoeuvring or hoteling (units: h). EF is the emission factor according to operational modes (cruising, manoeuvring, and hoteling) (units: g/kWh). Emission factors diverse for the main and auxiliary engines at the operational loads, and this difference is indicated separately in operational modes. As there are currently no locally derived emission factors for the Georgian coast, emission factors (NO_X, SO_2, CO_2, VOC, and PM) used in this study were taken from Entec, 2005 study (Entec, 2005). Specific fuel consumption (SFC) for main and auxiliary engines were derived from the Entec, 2002 study (Entec, 2002). Table 3 lists the emission factors according to operational modes for each type of ship (Entec, 2002, 2005, 2010).

SO_2 emissions occur in different amounts depending on the sulphur content of the fuel used. It was assumed that ships used MDO (Marine Diesel Oil) (with 1.0% sulfur content) and MGO (Marine Gas Oil) (with a sulfur content of 0.5%) for the main and auxiliary engines in all operating modes (cruising, manoeuvring, and hoteling) in the vicinity of Georgian ports since it was hard to find the type of fuel used in operation modes by ships. In this study, it was accepted that all auxiliary boilers use RO (Residual Oil) (with a sulphur content of 2.7%).

Table 3 Emission factors (Entec, 2002, 2005, 2010)

Ship types	Emission factors (C—cruising, M—manoeuvring, H—hoteling) (g/kWh)														
	NO_X			SO_2			CO_2			VOC			PM		
	C	M	H	C	M	H	C	M	H	C	M	H	C	M	H
Liquefied gas	8	8.9	8.8	12.4	12.5	6.9	816	818	795	0.31	0.67	0.6	1.03	1.55	1.2
Chemical	14.6	11.9	11.6	11	12.2	5.7	650	715	698	0.55	1.04	1	1.34	1.6	1.2
Tanker	13.3	11.2	11	11.7	12.7	7.8	690	745	730	0.5	1.1	1.1	1.43	1.82	1.5
Bulk dry	15.9	12.6	11.5	10.6	11.9	1.6	627	698	690	0.59	1.3	0.5	1.61	1.84	0.5
General cargo	14.5	11.9	11.4	10.9	12.1	1.2	649	715	691	0.54	1.03	0.5	1.28	1.59	0.4
Container	15.5	12.3	11.4	10.8	12	1.4	635	705	690	0.57	1.19	0.5	1.56	1.73	0.5
Ro-ro cargo	13.7	11.5	11.3	11.1	12.2	1.3	655	719	692	0.52	1.06	0.5	1.17	1.68	0.5
Passenger	11.9	10.6	11.2	11.8	12.6	1.5	697	747	696	0.46	0.97	0.5	0.81	1.71	0.5

Results and discussion

Ship emissions

Ship exhaust gas emissions (NO_X, CO_2, VOC, PM, and SO_2) at each studied port from the year of 2010 to 2018 were estimated and presented in Fig. 4. Calculated CO_2 and total greenhouse gas emissions from ships visiting the four ports for the year of 2018 were shown in Table 4. CO_2 emissions are responsible for 97% of total emissions and followed by NOx and SO_2 emissions with 2% for all the studied ports during the analysed periods. The GHG emissions from ships in the Batumi Port were 53.211 ton yr^{-1} CO_2, compared with 42.760 ton yr^{-1} in the Poti Sea Port, 11.609 ton yr^{-1} CO_2 in the Port of Kulevi, and 8.950 ton yr^{-1} CO_2 in the Port of Supsa. It was observed that the highest emissions (54.640 ton yr^{-1}) were produced in the Batumi Port with maximum ship visits in 2018. The Poti Sea Port followed as the second polluter with the amounts of 44.030 ton yr^{-1}, the Port of Kulevi (11.910 ton yr^{-1}), and the Port of Supsa (9.206 ton yr^{-1}) comes, respectively.

Containers and general cargo ships were dominant at emitting all the emissions through the 2010–2018 years in the Poti Sea Port. This was predicted since the Poti Sea Port was the central port in Georgia in the container traffic carrying of used and new vehicles for the Caucasus Region and Central Asia. Container and general cargo were the largest polluters in the Poti Sea Port and emitted the highest amount of exhaust gas emissions with more than 85% of total emissions. Tanker and general cargo vessels were accountable for the majority of calls in the Batumi Port since the port was the main transfer point of goods from the energy lines (oil, oil products, and coals). Liquefied gas, container, chemical, and bulk dry ships had the rest of 31% ship calls during years. Tanker and general cargo ships were the main pollutants with more than 70% of total emissions.

The Port of Kulevi registered the 170 ship calls annual average and tanker ships, chemical ships, and liquefied gas ships were the main visiting ships since the port was an oil and oil product handling port delivered from the Caspian Sea and Black Sea oil fields. At the Port of Kulevi, tanker ships emitted 67% of total emissions; chemical and liquefied gas ships followed it, respectively. The Port of Supsa had the minimum number of ship calls. The tanker ships were responsible for the port traffic and exhaust gas emissions for all studied years and this was because the port was an oil terminal transporting the crude oil from the Caspian Sea. The port had the lowest emission rates when compared with other ports.

Regarding emissions from ship types, tanker, general cargo, and container ships were the main polluters at all ports and these ships emitted almost 82% of all emissions in the Georgian ports. The highest level of emission was generated from tanker ships and produced nearly 34% of the total emissions; these ships were followed by general cargo with the amount of 27% as the second pollutant, and container with the amount of 22% as of the third pollutant of all shipping emissions. Briefly, the highest emissions came from general cargo, container, and tanker ships at all four Georgian ports. The same conclusion was reached by Alver et al. (2018), Deniz and Kilic (2009), Villalba and Gemechu

Fig. 4 Ship exhaust gas emissions (NO_X, CO_2, VOC, PM, and SO_2) from 2010 to 2018 at each studied port

Table 4 Calculated CO_2 and total greenhouse gas emissions from ships in ports

Georgian ports	Total ship calls in 2018	Container CO_2 emissions (ton/yr)	General cargo CO_2 emissions (ton/yr)	Tanker CO_2 emissions (ton/yr)	Chemical CO_2 emissions (ton/yr)	Bulk dry CO_2 emissions (ton/yr)	Liquefied gas CO_2 emissions (ton/yr)	Other ships CO_2 emissions (ton/yr)	Total CO_2 emissions (ton/yr)	Total greenhouse gas emissions (ton/yr)
The Poti Sea Port	568	27.692	8.211	2.634	724	2.121	0	1378	42.760	44.030
The Batumi Port	584	6.822	6.304	27.762	4.217	2.126	0	5.980	53.211	54.640
The Port of Kulevi	130	0	0	6.773	2.704	0	1.926	206	11.609	11.910
The Port of Supsa	98	0	0	8.950	0	0	0	0	8.950	9.206

(2011), and Saraçoglu et al. (2013) in their studies. Usually, each port study is different and has different emission results, as ship calls, ship types, ship size, engine power, and operation time vary widely. When looked at port emissions based on ship types, major sources of emissions were the container and general cargo ships for the Poti Sea Port, tanker, and general cargo ships for the Batumi Port, chemicals and tanker ships for the Port of Kulevi, and tankers for the Port of Supsa. The Poti Sea Port and the Batumi Port were the ports with the highest number of large ship visits, and this ship density partially explained the high average CO_2, NO_X, and SO_2 emissions per port call. Large ships mean to carry out long-term loading and unloading activities at berth with larger installed main and auxiliary engines.

For all the analysed ports and years, the greenhouse gas emissions emitted from vessels during the mode of cruising were 82% of the total amount, manoeuvring emissions were 5%, and hoteling 13% in operational modes. The emissions during the mode of cruising were greater than the modes of manoeuvring and hoteling because of 20-nm cruising distance. Emissions during the mode of manoeuvring were lesser than hoteling mode owing to long berthing times. Emissions released during the cruising, manoeuvring, and hoteling modes were shown in Fig. 5. Other studies have achieved alike consequences and stated that emissions during cruising mode account for about 50–80% of total greenhouse gas emissions (Fan et al., 2016; Chen et al., 2016; Saraçoglu et al., 2013) whilst some researches have found that emissions during hoteling mode reach 80% of total emissions (Maragkogianni & Papaefthimiou, 2015).

Comparison between estimated port emissions and other foreign ports

The ship exhaust gas emissions in Georgian ports were compared with other different region port emissions (in Table 5). Emissions at Georgian ports were comparable to those in the Black Sea and the Yellow Sea, and emission results appear to be close to each other, but less than those in Mediterranean. This could be attributed to differences in hoteling duration, cruising distance, navigation condition, and ship movements. Due to the similar number of ships arriving at ports, Georgian port emissions were at the same amount of emissions that occurred in the ports of Turkey located in Black Sea. Since there were fewer ships arriving in Georgian ports compared to

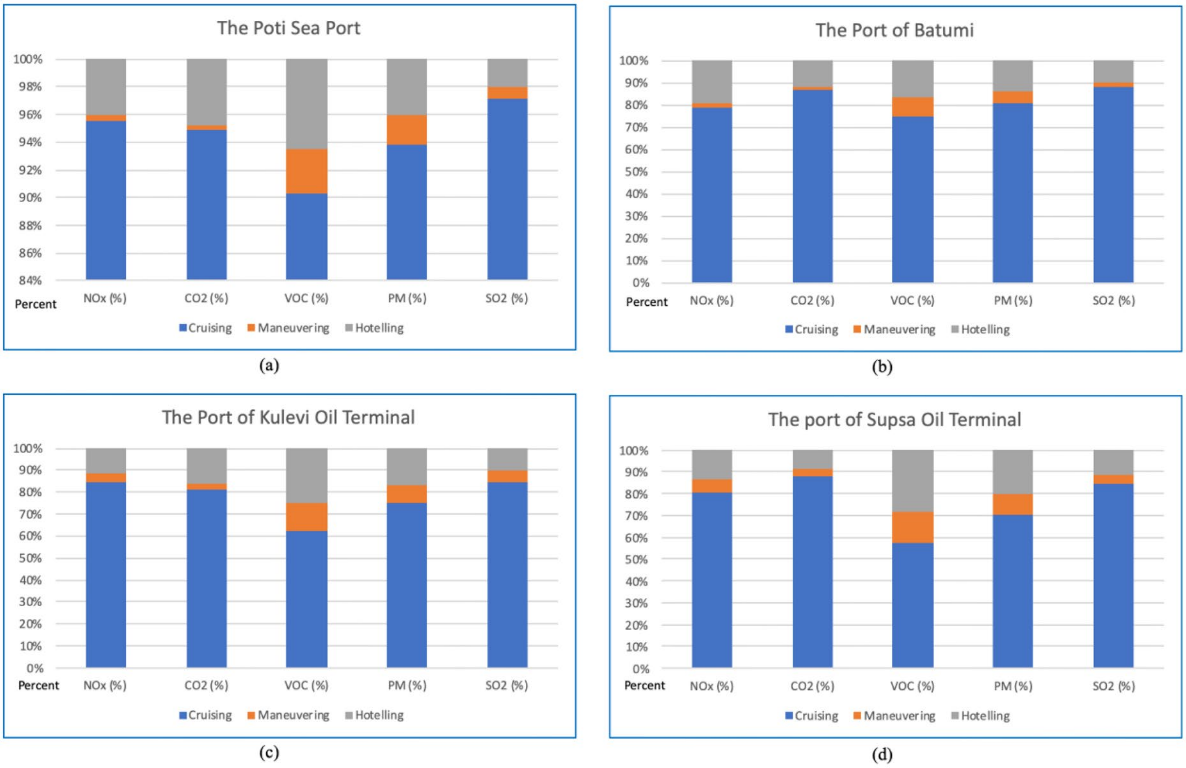

Fig. 5 Emissions during cruising, manoeuvring, and hoteling modes: (**a**) the Poti Sea Port, (**b**) the Batumi Port, (**c**) the Port of Kulevi, and (**d**) the Port of Supsa

the number of ships arriving at one of the ports in the Mediterranean or the Yellow Sea, the port emissions in Georgia were less than the port emissions in these seas. Emissions were higher in studies at international ports. The Batumi port emissions had one of the highest emissions amongst the analysed port emissions in the Black Sea. The NO_X and CO_2 emissions in the Ports of Poti and Batumi were more than those in Samsun, Shanghai, and Port of Bartin. SO_2 emissions in the Ports of Poti and Batumi were more than the SO_2 emissions in Port of Bartin, Shanghai Port, and the Civitavecchia Port because of the higher content of sulphur in marine fuels. PM emissions in the Batumi Port were more than the PM emissions in Port of Zonguldak, Trabzon Port, Port of Bartin, Port of Constanta, Shanghai, and the Civitavecchia Port. Other ports' (Port of Eregli, Port of Constanta, Izmir Port, Las Palmas Port, Yangshan Port, and Tianjin Port) total emissions were greater than these Georgian ports owing to the higher number of ship visits. The ship emissions at the Poti Sea Port and the Batumi Port were greater than those calculated at Samsun Port, Port of Bartin, Port of Zonguldak, Shanghai Port, and Civitavecchia Port notwithstanding the lower number of ship visits at Georgian ports (except for the Port of Kulevi and the Port of Supsa). This seems related to the fact that CO_2 and PM emissions of the ports were not included in the inventory. The total GHG emissions at the Batumi Port were similar to the Trabzon Port. Shipping pollutants estimated in this study were significantly lower than those at Yangshan Port, which is one of the world's largest ports (Song, 2014).

Sulphur oxide substance decline in the fuel from 3.5 to 0.5% were executed starting from January 1, 2020, globally (IMO, 2016). This new important implementation should be fulfilled and the harbour area should be monitored regularly and it is also one of the effective practices to reduce emissions.

Environmental costs

Air pollution generated from transport activities causes different types of external costs and these external costs are calculated with monetary valuation. The calculation of environmental costs contributes

Table 5 Comparison of port emissions on the different areas

Ports	Region	Study year	Ship calls	NOx (ton yr^{-1})	CO_2 (ton yr^{-1})	PM (ton yr^{-1})	SO_2 (ton yr^{-1})	Total emissions (ton yr^{-1})	Source
The Poti Sea Port, Georgia	Black Sea	2018	568	800	42.800	50	350	44.000	This study
The Batumi Port, Georgia	Black Sea	2018	584	900	53.200	60	440	54.600	This study
The Port of Kulevi, Georgia	Black Sea	2018	130	180	11.600	20	100	11.900	This study
The Port of Supsa, Georgia	Black Sea	2018	98	130	9.000	10	60	9.200	This study
Samsun Port, Turkey	Black Sea	2015	2.504	730	-	60	570	1.360	Alver et al. (2018)
Port of Zonguldak, Turkey	Black Sea	2019	615	820	45.700	44	350	46.914	Tokuslu (2020a)
Port of Eregli, Turkey	Black Sea	2019	708	1.281	67.639	70	505	69.495	Tokuslu (2020b)
Port of Constanta, Romania	Black Sea	2016	4.331	14.308	527.250	1.210	379	543.147	Nicolae et al. (2017)
Trabzon Port, Turkey	Black Sea	2018	679	906	52.160	54	409	53.529	Tokuslu (2020c)
Port of Bartin, Turkey	Black Sea	2018	360	551	30.347	28	230	31.156	Tokuslu (2020d)
Izmir Port, Turkey	Mediterranean	2007	2.806	1.900	82.800	170	1.400	86.270	Saraçoglu et al. (2013)
Las Palmas Port, Spain	Mediterranean	2011	3.183	4.200	208.700	340	1.400	214.640	Tichavska and Tovar (2015)
Civitavecchia Port, Italy	Mediterranean	2016	3.000	940	-	-	100	1.040	Gobbi et al. (2016)
Shanghai Port, China	Yellow Sea	2003	2.900	400	-	200	60	660	Yang et al. (2007)
Yangshan Port, China	Yellow Sea	2009	6.518	10.800	579.000	860	1.200	591.860	Song (2014)
Tianjin Port, China	Yellow Sea	2014	8.690	41.300	-	4.030	29.300	74.630	Chen et al. (2016)

the realisation of greener projects, motivates the using of technological improvements, and dictates the more effective use of resources. The environmental cost policy mainly focuses on five major emitting economies which are accounted for 55% of global GHG emissions in 2018: the European Union (EU), China, India, Japan, and the United States (Faostat, 2019; Olivier & Peters, 2019).

European Union projects have made significant contributions in the calculation and analysis of external (environmental) costs, and external costs are the foremost issue in the EU White Paper (European Commission, 2011), which states that these costs should be taken into consideration particularly for road, sea, and rail transport. The European pricing policy is precisely based on determining the external costs suitable for mode of transport and country to determine the general principles of transport pricing in the EU zone. There have been many numerous international studies and projects (AFFORD, 2001; HEATCO, 2005; INFRAS-IWW, 2004; CAFÉ, 2005; UNITE, 2003; GRACE, 2006; Life Cycle Cost Analysis; Reference Energy and Material System (REMS); External Costs of Energy (ExternE)) implemented to estimate and assess the external costs by EU, England, and US. Every country is using these projects to estimate its environmental costs.

The EU's environmental policy is in overall harmony with those of the International Maritime Organization (IMO) regulations and other countries environmental policies. The IMO has set out the principles on how to reduce ship-borne air emissions through the International Convention for the Prevention of Pollution from Ships (MARPOL) and its Annex VI focuses on reducing ship-borne air emissions such as NO_X, SO_X, PM, VOC, and other stratospheric ozone-depleting substances (IMO, 2009). MARPOL Annex VI has been signed and ratified by 99 countries around the world. These countries (including the European Union, China, India, Japan, and the United States) are having combined merchant fleets, which account for approximately 96.76% of the gross tonnage of the world trade fleet (IMO, 2021). These countries have to implement technical and operational practices to fulfil the requirements of Annex VI which covers the reduction of sulphur content in fuel, emission control areas (ECA), sulphur emission control areas (SECA), EEDI, and SEEMP measures (IMO, 2016).

Whilst MARPOL Annex VI describes the technical and operational measures to be taken, there is no directive on the calculation of environmental costs by IMO. Therefore, most of the participating countries do not have any studies on the calculation of environmental costs. Only developed countries (European Union, US, China, etc.) make calculations for their own regions and implement regional or local measures. It is considered that it will provide a future benefit if the countries that have already signed IMO and MARPOL take a joint step in this regard. This problem can be solved with the developed countries providing technical and financial support to the undeveloped countries. Otherwise, regional or local solutions cannot be expected to be permanent for a long time. This situation is also available for Georgia. Whilst Georgia was a party to the MARPOL and adopted its requirements and annexes, it could not sign the Annex VI. In addition to the lack of a national regulation or practice to control emissions from maritime and air pollution in territorial waters, it also lacks the financial and technical capacity like other littoral countries (Turkey, Romania, Bulgaria, Russia, and Ukraine). For this reason, it is very important that developed countries contribute to undeveloped countries on a regional basis (such as the Black Sea) in order to fulfil MARPOL requirements. Georgia should prepare the emission inventory of air emissions generated from shipping and have the necessary technical infrastructure until the signing the Annex VI. Therefore, this study will be a guiding study to start the implementation in this regard.

To estimate the environmental cost caused by air pollution, there are two different approaches: a bottom-up approach and top-down approach. In this study, the bottom-up approach was preferred to estimate the environmental costs of ship emissions in ports and three methodologies were used to compare the environmental costs of atmospheric pollutants per tonne: External Costs of Energy (ExternE), Clean Air for Europe (CAFE), and New Energy Externalities Development for Sustainability (NEEDS). The ExternE is an approach of calculating environmental costs using the monetary assessments of environmental burdens related to the energy sector, and it is applied to a wide range of different fossil, nuclear, and renewable fuel cycles for energy conservation options for each European member states (Realise, 2004; EC, 2005). CAFE is a project that applies the impact path approach to calculate air pollution costs (CAFE 2005). NEEDS is a project created to evaluate all costs and benefits of energy policies and future energy systems including all European sea regions using the EcoSense model (Korzhenevych et al., 2014). Values are expressed as damages per ton of each pollutant (NO_X, CO_2, SO_2, VOC, and PM) in studied ports. The environmental costs were calculated with the formula (4) of (EC, 2005; Bickel, 2006) which follows as:

$$C^s = \sum_j E_j^s \times C_j^s \tag{4}$$

C^s is the total environmental cost, E_j^s is the total emission amount of contaminant type j, and C_j^s is the cost of contaminant type j per tonne. The total environmental costs of Georgian ports were shown in Table 6. Whilst the lowest estimates were from the ExternE project (i.e., $13.25 million), it was estimated at €17.3 million from the CAFE application and €19.7 million from the NEEDS project. The average cost per ship call is $9.602, €12.535, and €14.288 for ExternE, CAFE, and NEEDS, respectively. These estimates can be compared with results found in other ports, such as Berechman and Tseng (2010) found the environmental cost of Kaohsiung port, was $119.2 million in 2010. Tzannatos (2010) calculated the Piraeus port emission costs in 2008–2009, which was €16.5 million or €10.4 million per cruise passenger. Maragkogianni and Papaefthimiou (2015) assessed the social cost of cruise ships in ports of Greece and estimated Katakolo, Corfu, Mykonos, Santorini, and Piraeus' were €11.88 million, €4.61 million, €2.84 million, €3.35 million, and €1.57 million, respectively. Song (2014) assessed the Yangshan port's social cost and eco-efficiency and the total social cost and eco-efficiency performance were estimated as $287 million and $36.528, respectively. Tokuslu (2020c) estimated the environmental cost of the Trabzon port emissions as $32 million and $47.039 per ship call.

In addition to the effects of ship emissions on human health, the damage they cause to the ecosystem is also very important. Understanding these damages will contribute to a full understanding of the damages that emissions cause mainly to the environment and the ecosystem. Exhaust gas emissions from ships (such as NO_X, SO_X, PM, VOC, and CO_2) have a detrimental effect on human health and marine ecosystems through eutrophication and acidification. Whilst SO_X and NO_X mainly contribute to ocean and soil acidification, the eutrophication, and climate change, PM have the potential to act more directly on human health and ecosystem. VOCs have effects of ozone on health and crop production. CO_2 has the global contaminant effect on environment and ecosystem. Emissions from shipping also contribute to ozone generation. Exposure to ozone has negative effects on the life of plants and marine life (IMO, 2000).

It should be pointed that there are various models that examine the effects of practices in marine ecosystem management and forecasting their future outcomes, but only few studies have developed the marine ecosystem management for ports (Deltares, 2015; Kolman, 2014; Nebot et al., 2017; Scherer & Asmus, 2016). Whilst each of these models share a common general approach, they differ in their details and intended practices. These models have been developed as a tool to improve marine ecosystem management which is an area of dynamic investigation and quick progress. Marine ecosystem forecasting models generally are TOPS, AMeDAS, GAINS, Maxent, EBM-DPSIR, the InVEST/HRA, and JSCOPE. They are mostly focused on sea life, fisheries, endemic and invasive species, planktons, climatic changes, water quality, and shipping emissions (Amann et al., 2011; Cofala et al., 2018; Miola et al., 2009; Relvas & Miranda, 2018; Patricio et al., 2016; Raudsepp et al., 2019; UNEP, 2006), but studies investigating the effects of emissions from ships on the marine ecosystem are insufficient.

Table 6 Estimation of total environmental costs (in 2018)

Ports	ExternE (million $)	CAFE (million €)		NEEDS (million €)
		Lower bound	Upper bound	
The Poti Sea Port	5.17	5.85	19.89	7.55
The Batumi Port	5.96	8.29	23.52	8.96
The Port of Kulevi	1.22	1.94	5.52	1.90
The Port of Supsa	0.90	1.22	3.47	1.30
Total costs	13.25	17.30	52.40	19.71

When these forecasting studies are examined, Ponce-Reyes et al. (2017) estimated the seven main ecosystem's extent using current climate data across Africa's Albertine Rift, and projected the potential distribution of ecosystem for 2050 and 2070. They found that high-altitude ecosystems and the endemic species were at immediate risk, owing to rapid predicted shrinkage in their suitable extent by 2050, and by 2070, 44% of the region could be climatically unsuitable for the current ecosystems. Jacoxa et al. (2020) reviewed statistical and dynamical marine ecosystem forecasting methods and highlighted examples of their application along U.S. coastlines for seasonal-to-interannual (1–24 month) prediction of properties ranging from coastal sea level to marine top predator distributions. Hafeez et al. (2021) developed a numerical framework to simulate different physical, chemical, and biological processes in a semi-enclosed coastal ecosystem management by integrating the WRF model with a 3D hydrodynamic and ecosystem model (Ise Bay Simulator). In the study, the performance of Automated Meteorological Data Acquisition System (AMeDAS) and WRF were equally good, and more than 80% of the variation in bottom dissolved oxygen for shallow water and more than 90% for deep water was reproduced. García-Onetti et al. (2018) examined the forecast of the Integrated and Ecosystem Based Management model for the port of Imbituba (southern Brazil). Forecasted model of DPSIR had been proposed and implemented in the study in a conceptual model. Nemani et al. (2009) presented an approach for monitoring and forecasting landscape level indicators of the condition of protected area ecosystems including changes in snow cover, vegetation phenology and productivity using the Terrestrial Observation and Prediction System (TOPS) which models ecosystem simulation to characterise ecosystem status and trends using operational satellite data, and microclimate mapping. Investigation the effects of emissions generated from ships on the marine ecosystem in Georgia will be a future study using one of these marine ecosystem management models. This study will aim to examine all the emission effects on the marine ecosystem in Georgian ports.

Uncertainties in ship emission estimates

The uncertainties of the ship emission were quantitatively assessed in this study. The uncertainties in the emission estimates were derived for each combination of pollutant type, ship type, ship size, engine power, and cruising route on four ports of Georgia. As summed up in Table 7, uncertainties in five pollutants were found with lower bounds of − 12.3 to − 33.9% and upper bound of 10.8 to 30.0% at 95% confidence intervals. These uncertainties were generally lower than those reported in other studies (about − 40 to 50% at 95% confidence intervals) (Ng et al., 2012; Ye, 2014). This can be ascribed to using activity-based methods for ship inventories. Many factors such as engine power, fuel quality, emission factors, ship movements, installed technologies, and meteorological parameters were included in uncertainty estimates, and each parameter had an effect on the accuracy of the emission inventory. In this study, it had been evaluated that the emission estimation uncertainties were mainly caused by the following:

1. Lack of ship information including fuel type and engine power. Processing incomplete information about the power of MEs, AEs, and boilers was the main source of the uncertainties of the ship activity-based method.
2. Small ships less than 400 GRT cruising (domestic movements) in the port area were not included in the emission estimation, causing the underestimation of the total ship emissions, but the relatively lower emission amounts of these ships were neglected since their numbers were not very high.
3. Uncertainty in emission factors. Since research studies on emission factors were not systematically carried out in the region, Entec Uk Limited methodology emission factors, which were regulated for European seas, had been adopted in the calculation.
4. Assignment of ship types, engine, and fuel type profiles according to the ship fleet used in the Entec UK Limited methodology.
5. The use of assumed and constant ship speeds and engine loads that were known to vary during ship operations and for different weather conditions. Discussions were held with port authorities to minimise uncertainties regarding the use of these default values as much as possible.
6. Some ships may have installed technologies to reduce SO_X (scrubbers) and NO_X (SCR) emissions. Since these ships were difficult to find in the studied ports, the emissions from these ships were calculated considering not having these technologies.

Table 7 Uncertainties in emission estimates

Ports	Pollutant	Emission estimate (ton)	Mean (ton)	95% CI	Uncertainty
The Poti Sea Port	NO_X	800	1.065	(810, 1.307)	(−23.9%, +22.7%)
	CO_2	42.800	55.096	(41.499, 68.603)	(−24.6%, +24.5%)
	VOC	30	41	(30,50)	(−26.8%, +21.9%)
	PM	50	63	(48, 77)	(−23.8%, +22.2%)
	SO_2	350	454	(342, 564)	(−24.6%, +24.2%)
The Batumi Port	NO_X	900	897	(787, 1.005)	(−12.3%, +12.1%)
	CO_2	53.200	54.726	(46.159, 62.838)	(−15.7%, +14.8%)
	VOC	40	37	(32, 41)	(−13.5%, +10.8%)
	PM	60	58	(50, 65)	(−13.8%, +12.1%)
	SO_2	440	457	(385, 521)	(−15.8%, +14.0%)
The Port of Kulevi	NO_X	180	242	(179, 305)	(−26.1%, +26.0%)
	CO_2	11.600	15.467	(11.608, 19.634)	(−24.9%, +26.9%)
	VOC	10	10	(8, 13)	(−20.0%, +30.0%)
	PM	20	17	(12, 21)	(−29.4%, +23.5%)
	SO_2	100	133	(98, 168)	(−26.3%, +26.3%)
The Port of Supsa	NO_X	130	130	(86, 152)	(−33.8%, +16.9%)
	CO_2	9.000	8.125	(5.363, 9.479)	(−33.9%, +16.7%)
	VOC	6	6	(4, 7)	(−33.3%, +16.7%)
	PM	10	9	(6, 11)	(−33.3%, +22.2%)
	SO_2	60	71	(47, 83)	(−33.8%, +16.9%)

7. The effects of current, wave, and wind were not taken into account since there was not enough data.

Future study is needed to improve the results of this study and to minimise the range of uncertainties. Further efforts to reduce uncertainties may include gathering more information on ship characteristics, the real power of ME, AE, type of fuels, and reliable local emission factors.

Conclusion

The present study was designed to estimate greenhouse gas emissions of NO_X, CO_2, VOC, PM, and SO_2 from ships based on bottom-up approach in four of the main ports of Georgia (the Poti Sea Port, the Batumi Port, the Port of Kulevi, and the Port of Supsa) from 2010 to 2018 for the first time. The results of this study indicated that the Batumi Port was the busiest and produced the highest emissions from the other ports. The Poti Sea Port followed as the second polluter, the Port of Kulevi, and the Port of Supsa came in order of. At the Poti Sea Port, emissions from container and general cargo ships emitted more than 85% of total emissions. At the Batumi Port emissions from tanker and general cargo ship signified more than 70% of total GHG emissions. At the Port of Kulevi, tanker and chemical ships produced the maximum amount of pollutants in 2018 with more than 81% of total GHG emissions. At the Port of Supsa tanker ships were responsible for all emissions in port and the port had the lowest emission rates when compared with other ports.

Regarding emissions from ship types, tankers, general cargo, and container ships were the main polluters at all ports and these ships emitted almost 82% of all emissions in the Georgian ports. The uppermost level of emission was created from tanker vessels and produced nearly 34% of the total emissions; these vessels were followed by general cargo with the amount of 27% as the second pollutant, and container with the amount of 22% as of the third pollutant of all shipping emissions. The greenhouse gas emissions emitted from ships during the mode of cruising were 82% of the total amount, manoeuvring emissions were 5%, and hoteling 13% in operational modes. The uncertainties of total emission estimation on all kinds of pollutants ranged from – 33.9 to 30.0% at 95% confidence intervals.

This study was the first for estimating shipping emissions and environmental costs of ships (ranging in total from $13.25 million to €19.1 million) on the east side of the Black Sea. This study created a shipping emission inventory on four main ports of Georgia. Ships calling into Georgian ports will have some environmental and health risks on people living close to ports and highly advised that all kinds of emission concentrations should be examined near the harbours regularly and that procedures should be implemented to decrease the emissions from shipping in the district of the ports. In our calculations, it has been shown that shipping emissions in ports of Georgia have a substantial portion in regional atmospheric emissions amongst other sources. Regardless, future research should continue to explore other emissions such as road, railway, and airport, and should be created a national emission inventory for the country and prepare the emission strategy paper or air pollution management plans including action strategies. In Georgia, there are no air quality protection regulations and NO_X, SO_2, and PM limits. This research will create a national shipping emissions inventory for Georgia.

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Author contribution Aydin Tokuslu: data curation, supervision, writing—reviewing and editing, roles/writing—original draft preparation, software, validation, conceptualisation, methodology, visualisation, investigation.

Availability of data and material The author does not have permission to share data.

Declarations

Ethics approval and consent to participate The author approves ethics approval and consent to participate.

Consent for publication The author consents for publication.

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