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The impact analysis of maritime autonomous surface ships (MASS) on ICT sector carbon footprint

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THE IMPACT ANALYSIS OF MARITIME AUTONOMOUS SURFACE SHIPS (MASS) ON ICT SECTOR CARBON FOOTPRINT

By

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature):

....

(Date):

....

Supervised by: **Professor Dr. Aykut I. Ölçer**

Supervisor's affiliation: **Director of Research Nippon Foundation Professorial Chair in Marine Technology and Innovation Head, Maritime Energy Management**

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Abstract

Title of Dissertation: **CRITICAL ANALYSIS TO INVESTIGATE THE IMPACT OF MARITIME AUTONOMOUS SURFACE SHIPS (MASS) ON ICT SECTOR CARBON FOOTPRINT**

Degree: **Master of Science**

The world is facing a visible effects of climate change caused by the accumulated greenhouse gas (GHG) and continuous release of carbon dioxide (CO2) into the atmosphere, primarily due to anthropogenic activities. The Fourth Industrial Revolution (4.0) has made it possible for the development and operation of MASS. This research work analyses and investigates the impact of MASS on the ICT sector carbon footprint. The analysis is on the basic concept of the ICT infrastructures MASS will leverage on to operate and the dependency of those infrastructures on electricity to function vis a vis the relationship between the kWh requirement and the CO2e emitted to generate 1kWh. Findings show that conventional ships have little impact on the CO2e on the ICT sector carbon footprint; however, the investigation revealed that MASS would significantly impact the growing ICT CO2e. However, MASS will help meet the IMO's 2050 target with the current trend and technological evaluation and the use of renewable energy in both the ICT and power sectors to generate electricity.

KEYWORDS: MASS, AIS, Autonomous ship, ICT, Carbon footprint, kWh, CO2e,

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List of Abbreviations

AI	=	Artificial Intelligence
AIS	=	Automatic Identification System
BAU	=	Business as usual
BT	=	Bitcoin Technology
CO2e	=	Carbon dioxide Emissions
EU	=	European Union
FTTN	=	Fibre to the node
GHG	=	Greenhouse Gas
GB	=	Gigabyte
ICT	=	Information Communication Technology
IMO	=	International Maritime Organization
kWh	=	Kilowatt/hour
kWh/m^2	=	Kilowatt-hour/square-meter
MASS	=	Maritime Autonomous Surface ship
MB	=	Megabyte
MSC	=	Maritime Safety Committee
NIMASA	=	Nigerian Maritime Administration and Safety Agency
PON	=	Passive Optical Network
POS	=	Proof of Stake
POW	=	Proof of Work
SCC	=	Shore Command Centre
SOLAS	=	The International Convention for Safety of Life at Sea
VHF	=	Very high frequency
VSAT	=	Very small aperture terminal
VTS	=	Vessel Traffic Services

Chapter 1 - Introduction

1.1 Background Information

Greenhouse gas is the leading cause of climate change, consisting of natural and anthropogenic GHG; however, studies suggest that the leading drivers for climate change are human activities (anthropogenic). Such activities lead to the global temperature rise that affects the environment and humans. A decrease in GHG from human activities should be the focal point in keeping the earth's temperature within the safe limit (Nguyen, 2020). Records show that Carbon dioxide emissions (CO_2e) from shipping continue to increase, even in the face of continuous implementation of various global, regional and local initiatives; in April 2018, the Initial GHG strategy for the reduction of GHG emissions from international shipping was adopted by the International Maritime Organization (IMO); the strategy demand an urgent action for the abatement of maritime GHG emissions from business as usual (BAU) to at least 50% by 2050 reduction as compared to 2008 and gradually phase it out entirely by the end of century (Christodoulou et al., 2021).

The international community under the Paris Agreement came up with a legally binding international treaty on climate change during the meeting of COP21 in Paris on 12 December 2015. As of February 2021, 194 states and the European Union (EU) have signed the agreement, 190 states and the EU, representing about 97% of global greenhouse gas emissions, have ratified the agreement. Individual EU member states are responsible for ratifying the Paris Agreement. The agreement entered into force on 14 November 2016 (United Nations, 2021).

The Paris Agreement did not specifically include international shipping, but IMO as a regulatory body of the sector, is committed to reducing GHG emissions from international ships through an IMO instrument, MARPOL Annex VI, which was first adopted in 1997 and came into force in 2005 (IMO, 2019b). The Fourth IMO GHG study shows that emissions had increased from 2.76% in 2012 to 2.89% in 2018; however, it is clear that the emission in 2020 and 2021 will be low due to the impact of COVID-19, although it will be too early to measure the impact of COVID-19 on emission quantitatively. (IMO 2021).

The rise in CO_2e raises some concern on how to reduce CO_2e from international shipping in line with the Paris agreement. The Sixth Assessment Report of Climate Change 2021, that set a target to hold the global warming limit to well below 2 degrees, preferably 1.5 degrees Celsius as compared to pre-industrial levels. The report state that the consequences of missing these aims will lead to reaching Global Warming Level (GWLs) of 3°C or 4°C by the end of the century (IPCC Report, 2021).

In 2018 initial IMO strategy was adopted "The initial IMO GHG Strategy, adopted in 2018, sets ambitious targets to reduce GHG emission from ships to 50% by 2050, compared to 2008, and reduce the carbon intensity of international shipping by 40% by 2030 compared to 2008" (IMO, 2019c)

In an IMO's strategic plan (2018-2023), "***Integrate new and advanced technologies in the regulatory framework***", which involved the benefits derived from the new and advancing technologies and the impact on the environment (IMO, 2019a). Leveraging these technologies, ships are now being automated at different degrees or levels to improve efficiency and reduce CO_2e while becoming safer.

The IMO Maritime Safety Committee (MSC) defined the four(4) levels of ship automation as follows;

The first level of automation "***Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control***".

Second level of automation "***Remotely controlled ship with seafarers on board: The Ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions***".

Third level of automation "***Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board***".

Fourth level of automation "***Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself***". (IMO, 2019a).

The Fourth Industrial Revolution's impact makes the autonomous ships actualization a reality; several prototypes have been tested in recent years (Nguyen, 2020). However, Maritime Autonomous Surface Ship (MASS) requires connectivity and other Information Communication Technology (ICT) infrastructures to be operational (Hoyhtya et al., 2017)

It is clear that irrespective of the Ship's automation level, ICT equipment will be used to achieve the said objective. This equipment or devices on board ships or on shores will use power to operate hence will have a carbon footprint from the Ship to the shore using these devices.

The ICT sector covers computers, peripherals equipment, connectivity of networks, telecommunications equipment and data centres.

For example, a network with fibre to the node (FTTN) would consume 176 kWh of electricity to transmit 10Mbit/s for a year, leaving a carbon footprint of 192kg of CO2e per year, while Passive Optical Network (PON) providing access of 10Mbit/s will consume 101 kWh of electricity and result in 109kg of CO2e per year (Baliga et al., 2009). It is estimated that a single email will generate 4gCO2e while an email with an attachment will generate 50gCO2e taking account of the transmission and storage of the email (ICT carbon footprint. 2016).

Another research shows that streaming video for an hour will result in 0.42 kg of CO2e emitted (Schuler, 2016).

1.2 Problem statement/motivation

The IMO's goal to decarbonize international shipping welcomes the use of technology such as ICT to enhance the process to meet the Paris agreement target. IMO plays a vital role in the fight against climate change in line with the UN sustainable development goal 13 (IMO, 2019b). One of the promising features of MASS is energy efficiency (EE) and the reduction of CO2e from ships using renewable energy or electricity (Nguyen, 2020). MASS at the different levels of automation as defined by the MSC requires ICT devices and connectivity to operate; the conventional ships, to some extent, require some connectivity and ICT devices for operational purposes; depending on the degree or level of automation as defined by MSC, the requirement may vary.

IMO has several ambitious targets to reduce CO2e from international shipping, the level of ambition in 2050 is to reduce CO2 by 50% using 2008 as a base year (IMO, 2019b). The ambitious goal has mounted pressure in ship construction and processes to embrace technological advancement and the use of ICT devices to achieve automation to enhance energy efficiency.

The ICT sector has seen massive growth in the last 70 years, with large parts of the economy not yet digitised and emerging economies entering the market; historically, ICT sector CO_2e has grown continuously alongside global emissions (Freitag et al., 2020). The growing ICT sector has currently come under the light as one of the significant contributors to GHG emissions.

This research work is derived from the motivation to investigate the carbon footprint of MASS on the ICT sector while analysing the carbon footprint of conventional ships on the ICT sector currently.

1.3 Aim and objectives

This research work is geared towards investigating the implications of MASS on the ICT sector carbon footprint. The assessment will give an insight into the contribution of MASS to the fast-growing ICT sector CO_2e. The objectives are as follows;

- Collect and evaluate the impact of AIS signals transmission and data generated on various types of conventional ships in the ICT sector.
- To identify the energy (kWh) requirement to transmit data over the ICT infrastructure
- Determine the CO_2e emitted to generate kWh of electricity.
- Collect and evaluate data generated during MASS operation
- Analyse, synthesis and forecast the possible impact of MASS operation on ICT sector carbon footprint

1.4 Research questions and hypothesis

This research work will answer the following research questions.

What is the connectivity and energy requirements to operate MASS?

Does MASS require a cloud storage system to operate? If yes, how much data space and energy is required?

Does MASS require cybersecurity to operate? If yes, what is the energy requirement for cybersecurity?

Does MASS require a command and control centre to operate? If yes, what is the energy requirement needed to run the centre?

Different types of conventional ships are selected for analysis. Subsequently, a MASS model will be built based on the hypothesis that MASS will require offshore, onshore connectivity, cloud storage, command and control centre to operate and will impact the ICT sector carbon footprint.

1.5 Research scope

The research work focuses on the connectivity and the data generated by MASS and quantifies the carbon footprint it will generate for the ICT sector; a model will be developed to calculate the potential carbon footprint of MASS.

This research work will not cover the devices life cycle analysis, which takes account of the product life cycle from manufacturing processes to the end of the device life cycle carbon footprint but only compute the carbon footprint of the connectivity and data generated.

1.6 Research outline

The outline of the research work is illustrated in Figure 1.

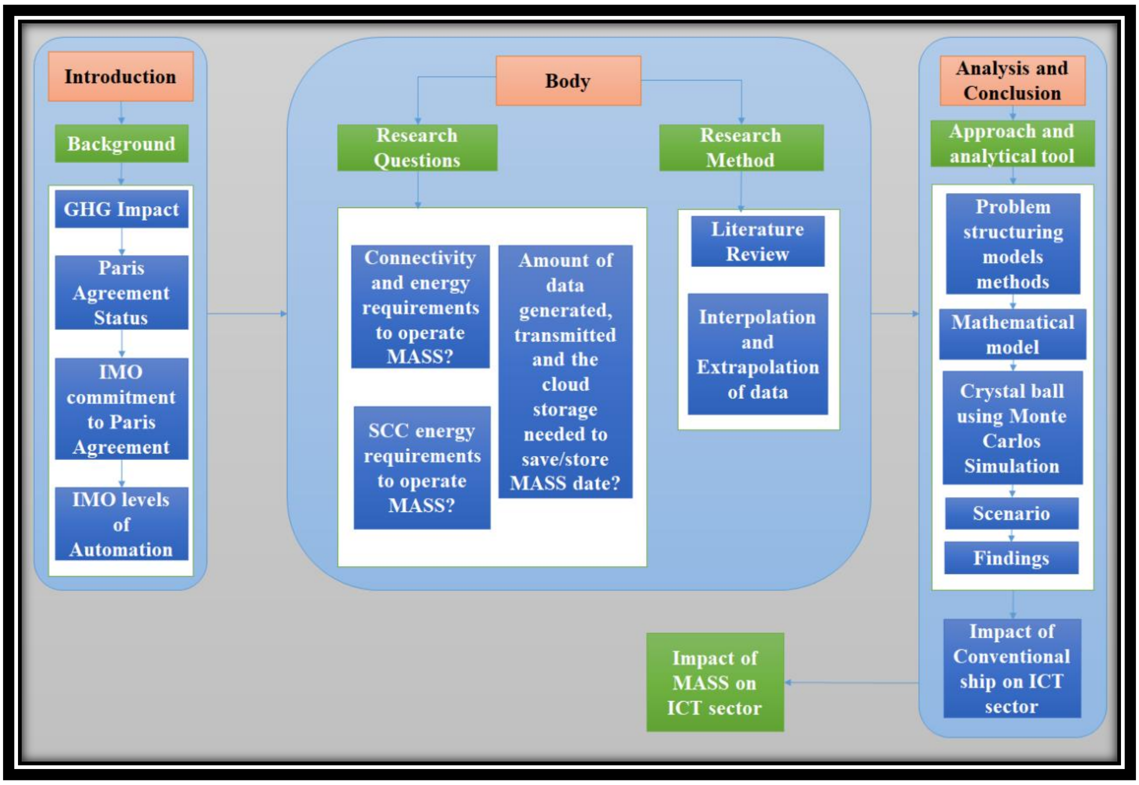

Figure 1. Research outline

1.7 Dissertation Structure.

This dissertation is organized into 5 chapters and includes the following elements;

- Chapter I: Introduction.
  - This chapter covers the background information, problem and motivation, aims and objectives, research question, scope and outline.
- Chapter II: Literature Review.
  - This chapter analysis various articles, reports and other internet sources.
- Chapter III: Methodology (Problem Models & Mathematical Framework).
  - This chapter explain the method, illustration and tools used to arrive at the result.
- Chapter IV: Discussions, Scenario and findings
  - This chapter consist of the detailed discussion of the result and scenario based on reasonable assumptions.
- Chapter V: Conclusions and Future Research
  - This chapter make conclusion based on the findings and recommend for future work to be carried out on the areas beyond the scope of the research work.

Chapter 2 -Literature review

2.1 General Overview.

Autonomous systems at different levels of automation such as cars, robots, drones, and ships leverage on ICT devices, data centres and connectivity and, to some extent, command and control centres. They will also need data transmission and remote sensors for operational purposes. (Marko & Jussi Martio, 2020).

2.2 ICT Sector and Carbon Footprint.

According to the European Framework Initiative for Energy & Environmental Efficiency in 2016, the ICT carbon footprint is the amount of CO2e released into the atmosphere by the ICT sector activities. ICT sector accounts for 8-10% of the European electricity consumption and up to 4% of its carbon emissions (ICT carbon footprint. 2016). In 2012 the ICT sector consumed about 4.7% of the world's electrical energy (Gelenbe & Caseau, 2015). According to Belkhir & Elmeligi (2018) revealed that the contribution of the ICT sector to global carbon footprint grows from 1.6% in 2007 to 3.6% in 2018 of the total global CO2e; this is more than double within 11 years.

Fettweis and Zimmermann in 2008 stated that ICT systems are associated with 2% of total global CO2 emissions, as cited by Magazzino et al. (2021); their findings suggest that ICT displays a positive and significant effect on electricity demand, which in turn translates into more CO2e. Without any energy efficiency measures, the ICT industry could use 20% of all electricity and emit up to 5.5% of the world's carbon emissions by 2025 (Andrae, 2017).

The ICT sector has a green image because it seems to provide solutions to some environmental problems such as electronic documents (no need to print), Remote working, example during COVID-19 pandemic, a system where an employee can work from outside the workplace of work which has many advantages such as an improved work-life balance, increased productivity, savings of CO2e and so on. Though ICT provides some solutions to environmental problems, it also creates some negative externalities, one of these problems is the energy consumption of ICT devices.

According to Bart (2013) the total sum of electricity consumption of communication networks, data centres and personal computers is growing at a fast rate annually, and this amounts to about 930 TWh of electricity consumed in 2012.

Another study on data networks by Muriel et al. (2017) reveal that data network which form the backbone of the ICT sector, consumed around 185 TWh globally in 2015.

Casual observation may suggest that ICT sector growth and development have increased productivity and energy efficiency, thus reducing CO2 emissions (Faisal et al., 2020). However, as the demand for and supply of ICT product and services increase it may result in more CO2 emissions. (Lee & Brahmasrene, 2014). In a more recent report published by Ericsson Group, the consensus was that the ICT sector's carbon footprint could be reduced by over 80 percent if all electricity consumed came from renewable energy sources (Ericsson Group, 2020).

According to CISCO system inc, "***data usage on the internet is estimated to be 20,151 PetaBytes per month; this is equivalent to 241 billion GB per year. Applying these figures to the average power estimate yields a figure of 5.12 kWh per GB***" (Costenaro & Duer, 2012). However, a study showed an estimated energy consumption (kWh/GB) in 2010 was 12.3kwh/GB, which is within the range estimated by Andrae and Edler within their study (6–15 kWh/GB) (Pihkola et al., 2018).

Malmodin et al. (2014) stated that "data transmission and IP core network (0.08 kWh per gigabyte [GB]) is based on data volumes from 2010 and can be compared to the figure (0.2 kWh/GB) presented by Coroama and colleagues (2013)."

The American Council for an Energy-Efficient Economy reached a lower number of 3.1 kWh/GB to save data on cloud storage. (Magazine, 2017).

2.3 Energy generation, consumption and carbon footprint.

Energy is used by many different equipment and devices to enable communication and transmission of data from point A to B. On average, to generate electricity per hour on a global electricity mix, the amount of CO2 emissions is (0.6 kg CO2e/kWh) while Sweden mix is (0.06 kg CO2e/kWh) with a relatively low GHG-emitting electricity (Malmodin et al., 2014).

Today's energy systems are mainly dependent on fossil fuels; even though the Nordic system, especially Sweden, with high renewable in the mixed grid system, there is still a carbon footprint in the electricity generation. The fuel type and source of energy greatly influenced the CO2e/kWh. (Kristinsdóttir et al., 2013).

2.4 ICT in Maritime Sector.

Critical look at conventional ships transmitting Automatic Identification System (AIS) signals via ICT infrastructures will confirmed that it will generates carbon footprint on the ICT sector.

The AIS component is connected through the on board communication network device (Transponder) to permanently or frequently connected to onshore communication infrastructures, e.g. through satellite links. This advance in ship technology enhances the monitoring and control capabilities, both on board and from shore. (Sahay et al., 2019).

AIS use on board ships is obligatory under the International Convention for the Safety of Life at Sea, Chapter V, Regulation 19 convention (SOLAS). The primary aim is to make navigation safer as a tool to avoid a collision at sea. Exchange data with shore-based facilities are made possible via AIS. Connectivity is established based on the capability of AIS to transmit data between vessels, satellite networks and maritime surveillance centres (Le Tixerant et al., 2018)

AIS uses marine VHF channels, and each ship is equipped with an AIS transponder that sends out a packet of information every few seconds with information about the ship and its voyage. A typical Class A AIS transponder broadcasts the voyage and ship information every 2 to 10 seconds while underway and every 3 minutes while at anchor (Milltaech Marine, 2021). The size of the AIS signal data is 50 bytes (Traffic, 2021). Figure 2. shows the pictorial representation of AIS connectivity between ships and AIS shore base station.

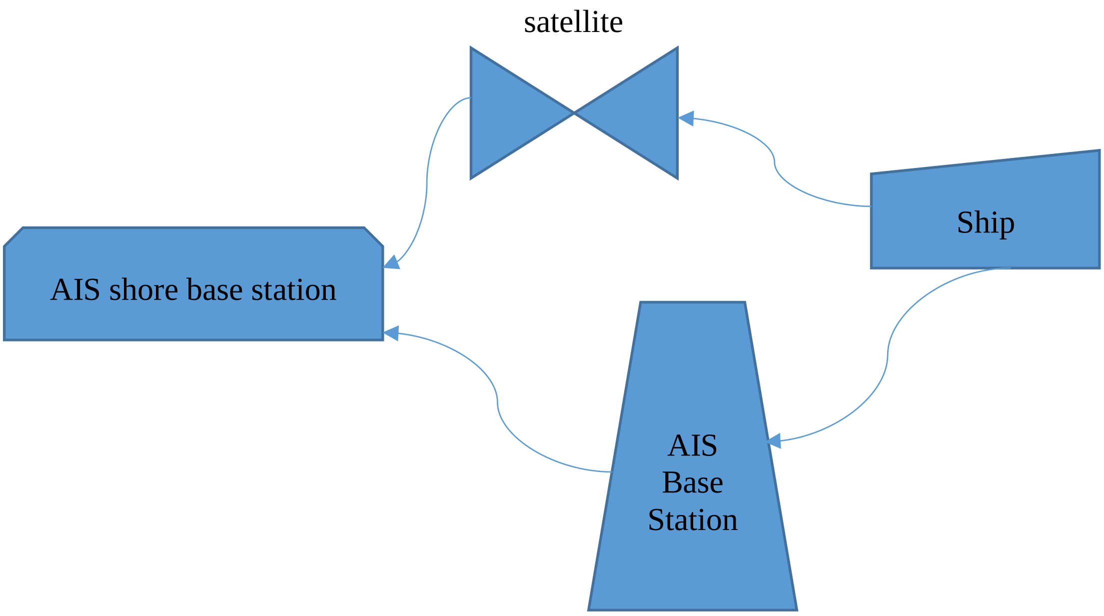

Figure 2. Overview of AIS connectivity.

2.5 Autonomous ship

The advancement of technology spanning from digitalization, big data and Artificial Intelligence (AI) have matured to a level where autonomous ships are imminent. The development of technology for controlling ships from shore has been progressing at a rapid pace. The International Maritime Organization (IMO) has to adopt one of its seven Strategic Directions to be pursued for the 2018-2023 timeframe, "***Integrate new and advancing technologies in the regulatory framework***". MASS will be an innovation that disrupts and induces a paradigm shift in an international shipping industry and maritime transport domain. (Roh, 2018)

The introduction of MASS to the maritime transport domain will increase the capacity of data transmission. Study shows that "***If Internet capacity is increased, the energy consumption, and consequently the greenhouse footprint of the Internet will also increase***" (Baliga et al., 2009).

The maritime industry has seen significant technological shifts over the years; even before the COVID-19, the maritime is in the era of digitalization, connectivity, data and optimization. The current situation has further strengthened the actualization of autonomous ships. The development of autonomous ship systems is primarily driven by the need to improve sustainability and zero-carbon shipping. The shift from conventional to autonomous shipping will significantly impact how ships interact with their surroundings. Automation ships are expected to increase digital communication in ports and fairways. A significant shift is expected from voice communication to digital information exchanges between automated entities and autonomous ships. The driving technologies for autonomous ship systems are largely untested. However, connectivity and data exchange will play a vital role in actualizing autonomous ships. The autonomous ship system must be regarded as a cyber-physical system of systems that consists of many physical and virtual components both onshore and on board the ship connected. These physical and virtual components interact with each other, and they are connected and communicate. (Wennersberg et al., 2020).

The technology readiness in telecommunications, ship to shore connectivity has improved to the point where remote operation of vessels is becoming a reality. These technologies also bring about threats such as cyber-security; as usage of the connectivity expands into shipping equipment and operations, a large scale of data will be captured and stored in secure servers for reference and analysis purposes. Hence cybersecurity becomes of utmost importance to handle within the digital environment. Both Port Authorities and Control Centres need to be prepared to handle existing and emerging cyber threats from criminals with the intent on shutting down or hijacking the ship (Kenyon et al., 2019).

Figure 3 bellow shows the various components involved in MASS

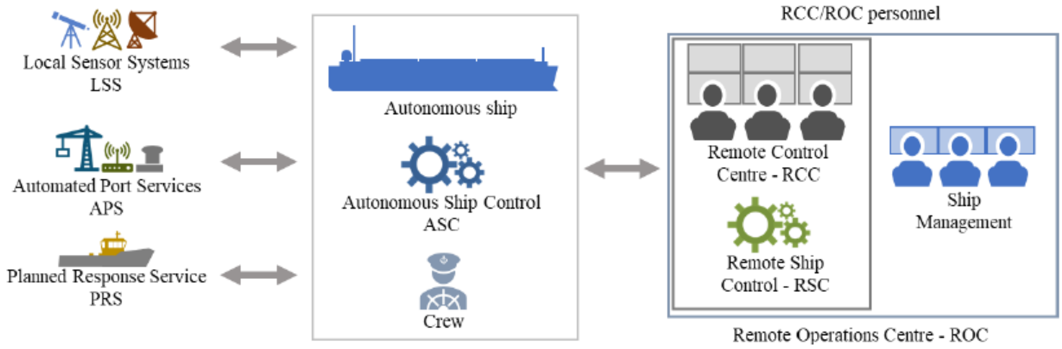

Figure 3. Components of MASS Connectivity (Wennersberg et al., 2020).

2.6 Cyber Security

Conventional ships and other vessels may seem to be like unusual targets for cyber-attacks, but with the emergence of MASS and satellite communications, hackers will have a new playground for an attack. Maritime cybersecurity can be defined as "the collection of tools, policies, security concepts, security safeguards, guidelines, risk management approaches, actions, training, best practices, assurance, and technologies used to protect maritime organizations, their vessels, and their cyber environment" (Secure, 2021) One of the high profile cyber-attack incidents that happened In June 2017 to a Danish shipping giant Maersk sent the company dark after being hit with NotPetya. This attack cost the company about $300 million and lost most of its data (Secure, 2021).

According to RESOLUTION MSC.428(98), which was adopted on 16 June 2017 that " Administrations, classification societies, shipowners and ship operators, ship agents, equipment manufacturers, service providers, ports and port facilities, and all other maritime industry stakeholders should expedite work towards safeguarding shipping from current and emerging cyber threats and vulnerabilities" (IMO 2017)

2.6.1 Blockchain Technology for MASS Cybersecurity

Connectivity is a critical component of MASS; communication needs to be secured and supported by multiple systems. Secure communication and connectivity are mandatory to avoid intruders interfering with ships operations or taking control of the ship. Blockchain technology (BT) security-based is a suitable candidate to secure communication and data storage exchanged between MASS and shore control centres. Implementation and adoption of BT will eliminate some threats for ships communication and play a significant role in identification and certification, ensuring data integrity and information security is achieved and maintained. MASS and BT are among the top technologies that will change the maritime industry to improve data sharing. In August 2018, a container was processed with a new blockchain-based bill of lading at the Port of Koper, Slovenia. The bill of lading for the shipment has been issued electronically and transferred with the secure and reliable public blockchain network (Petković et al., 2019).

Blockchain can easily be defined as a digital ledger or distributed system that records transactions of value using a cryptographic hash function that is innately resistant to alteration. Blockchain maintains a constantly growing list of blocks that are secured from tampering. Blocks contain a link to the previous block, as well as a timestamp. Blockchain is designed to have smart contracts that can be implemented without human interaction, and the data is not easily altered. The Smart contract is a digital code that is executed over different nodes to maintain the consensus of the result of the contract (Mylrea & Gourisetti, Aug 2018).

There are several reasons for energy consumption in blockchain, one of the reasons is an iterative process termed cryptographic hashing, which is when each block is encoded in an iterative process. When each block is encoded in an iterative process termed as cryptographic hashing, this results in high processing power that demands high energy (Nair et al., 2020).

The first blockchain application is Bitcoin, the world’s first cryptocurrency created in the year 2009, developed by Nakamoto. He proposed a distributive electronic cash payment system that uses Peer to Peer communication of anonymous internet users. During transactions, nodes come into existence that collects all the outgoing transactions in a single block, and these particular nodes are also responsible for the validation of the process. This process takes about 10 minutes for block validation and inclusion in the blockchain. The validator nodes are known as miners. The blockchain uses a process called proof-of-work (PoW), which is maximized and relies on the network resources to protect it from malicious attackers, and it consumes energy (Nair et al., 2020).

Figure 4 shows the pictorial representation blockchain cybersecurity architecture of MASS using bitcoin concept.

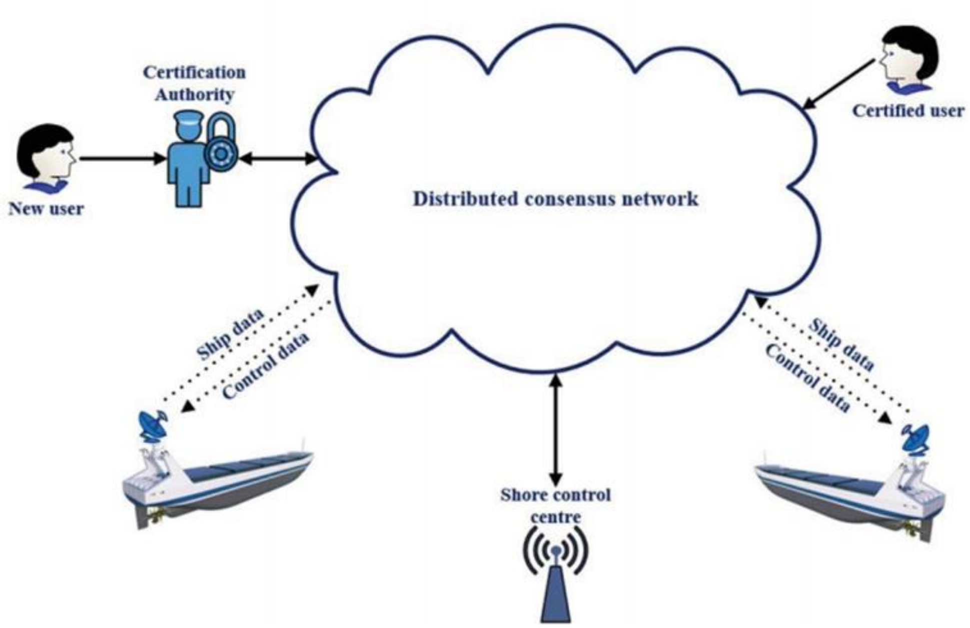

Figure 4. Bitcoin security architecture (Nair et al., 2020).

Bitcoin as a decentralized cashless payment system was introduced in early 2009, and it is now widely accepted by over 100,000 merchants and vendors worldwide. Each transaction is compiled into a 'block' that requires a computationally demanding proof-of-work to be resolved, which in turn uses large amounts of electricity. It is estimated that Bitcoin usage emits 33.5 MtCO2e annually as of May 2018 (Mora et al., 2018). The constant criticism of PoW led to an alternative algorithm being proposed, often known as proof of stake (PoS). PoS replaces iterative computational work with a random selection process. The probability of generating a block depends on what the stake nodes have invested in the system. This approach can potentially result in faster blockchains and have much lower electricity consumption (Andoni et al., 2019).

It is important to note that the high energy consumption of PoW blockchains is neither the result of inefficient algorithms nor of outdated hardware; such blockchains are ***''energy-intensive by design''*** (Sedlmeir et al., 2020).

According to Bill Gate, "***Bitcoin uses more electricity per transaction than any other method known to mankind***" (Ponciano, 2019)

Digiconomist reported that a single Bitcoin average energy consumption per transaction compared to VISA as of July 13, 2021, is 1752.79 kWh, while 100,000 VISA card transactions are 148.63kWh (Digiconomist, 2021).

"***According to the Cambridge Centre for Alternative Finance (CCAF), Bitcoin currently consumes around 110 Terawatt Hours per year — 0.55% of global electricity production, or roughly equivalent to the annual energy draw of small countries like Malaysia or Sweden***" (Carter, 2021).

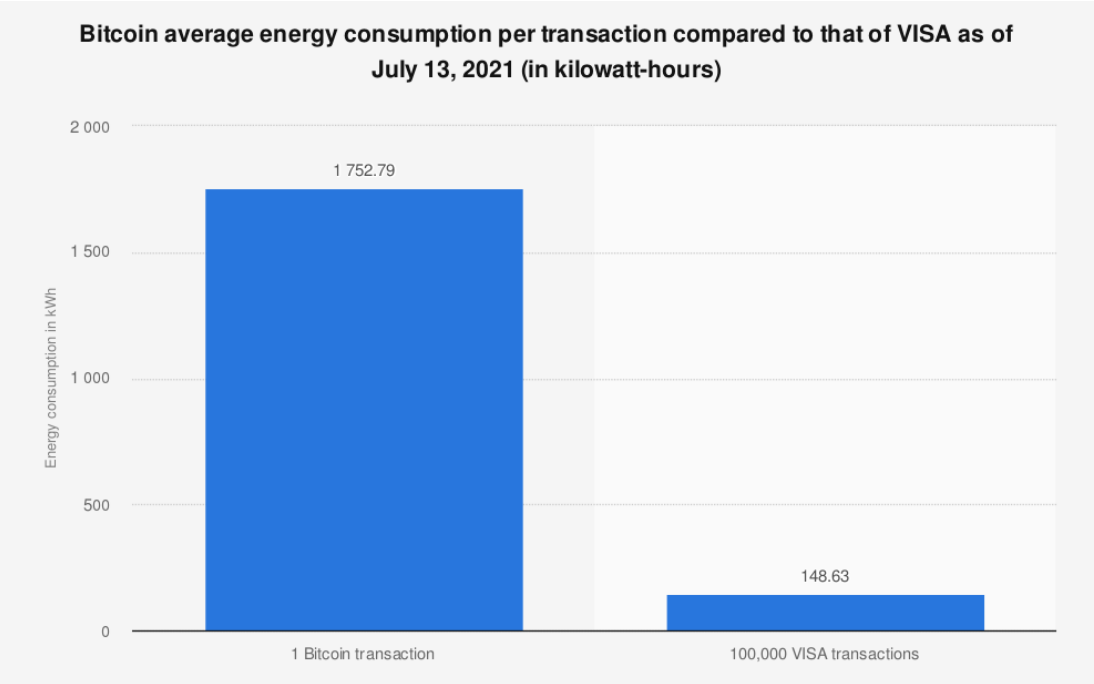

Figure 5. Bitcoin energy consumption (Statista, 2021).

One of the options to securely protect MASS against cyber-attacks is to use the principle and technology of blockchain, just like bitcoin. However, another alternative might be used, but whichever technology might be deployed will consume energy.

2.7 Shore Command Centre (SCC) Building and Equipment

Autonomous ships, also known as MASS, are becoming a reality in the maritime domain, promising increased efficiency and sustainability. An autonomous ship is a vessel with the possibility of operating on one or more Levels of Automation as defined by the IMO's MSC (Dybvik et al., 2020)

The SCC is needed to monitor one or more autonomous ships remotely and to intervene in their navigation, if necessary. The primary purpose of SCCs is to provide the ability to monitor and take control of autonomous vessels from a remote location, especially in a critical situation, as means to avoid collisions that are outside the capability of the automatic navigation system. SCC will replace the traditional bridge with remote operators that could be called “virtual captains,” able to steer single or multiple autonomous ships simultaneously. (Dybvik et al., 2020).

The Shore Control Centre acts as a continuously manned supervisory station for monitoring and controlling a fleet of autonomous ships. Most of the time, the ships are operating without any need for intervention from the shore if the autonomous ship is completely unmanned and is at level 4 of the IMO’s level of automation. In cases of unforeseen circumstances where the automated on board intelligence systems cannot safely handle a situation, assistance will be provided from the SCC. Further tasks which need to be taken over by the shore-based personnel include, e.g. very high frequency (VHF) communication, vessel traffic service (VTS) reporting, on board energy management, condition monitoring and maintenance planning. (Porathe et al., 2013).

SCC is necessary for remote monitoring during autonomous execution in case of minor changes, such as changing route or speed (Amro et al., 2021).

Very small aperture terminal (VSAT) services are catalysts for the actualization of autonomous ships. For example Inmarsat Fleet Broadband provides a global connectivity service that is used by the ship’s crew for ad hoc Internet access and IP Telephony; the Fleet Xpress maximum uplink speed (ship to shore) is about 5 Mbps, and the maximum downlink speed (shore to ship) is 50 Mbps (Inmarsat Global, 2021).

Autonomous ships will generate data in any voyage engaged; the data will be processed by stream processing software and uploaded to the onshore cloud system in real-time via the ship’s broadband service. The onshore cloud system will also be a repository for the ship’s data collected and will provide the environment for ship applications software development and deployment (Koroneos, 2017).

To understand the amount of data MASS will generate, we have to look at the car industry, Simon (2021), reported that Autonomous cars generate more than 300 TB of data per year. In contrast, another report published by kdespagniqz (2015), claimed that autonomous cars send 25 gigabytes of data to the cloud system every hour.

Another study conducted by McKinsey and Company that it is estimated that the amount of data an autonomous car will generate every hour is four (4) terabytes (Burkacky et al., 2018)

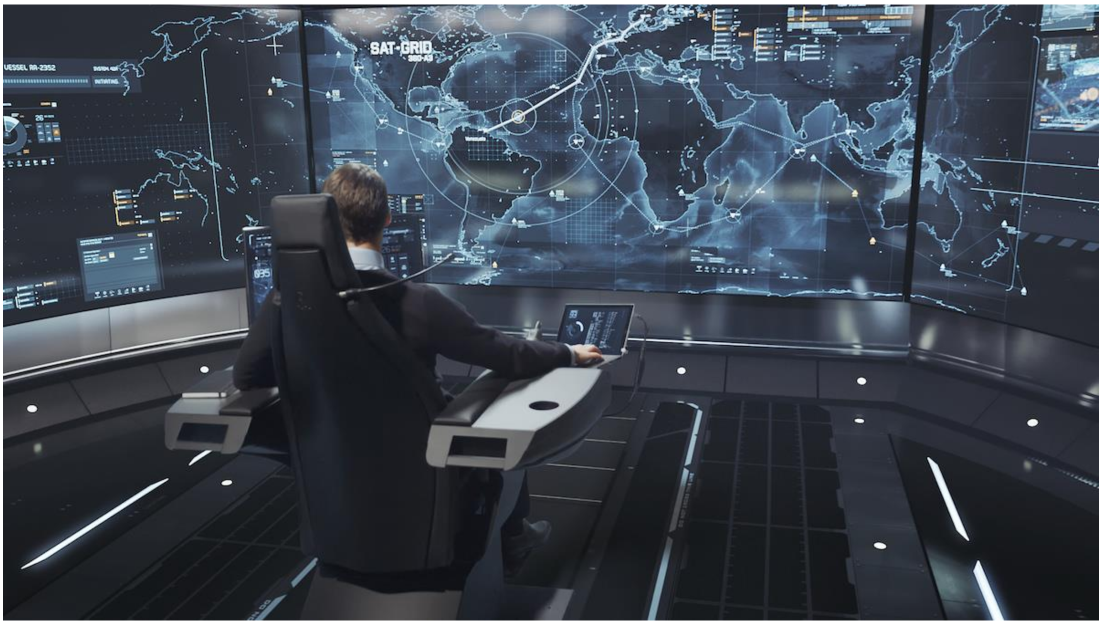

Figure 6. Rolls Royce Shore Command and Centre (Mike Schuler, 2016).

Another aspect of SCC to be considered is the power requirement to operate; the power/energy consumption of each SCC will vary depending on the size and number of electrical equipment at the centre. To measure the actual energy consumption of SCC will be difficult, but we will have to look at some literature where the energy consumption of both residential and non-residential buildings has been analysed to have an idea of the typical energy consumption of a particular building depending on its purpose.

According to the European Commission, the energy use in non-residential buildings is 40% more energy-intensive than residential buildings (250 kWh/m^2 compared to 180 kWh/m^2) per year. Italy, Malta and Estonia use by far the largest amount of energy per m^2 which is more than 1.5 times higher than the EU average. Other countries use between 200 and 300 kWh per m^2 per year (European Commission, 2020)

Research work by Guillem (2011) shows that an average Swedish building was 99 kWh/m^2 per year.

A comprehensive energy consumption analysis per unit area of office, hospital and school buildings was conducted in China, and it was found out that the energy consumption varies from 26.76 to 475.27 kWh/m^2; from 91.94 to 329.94 kWh/m^2 per year and from 50.85 to 204.30 kWh/m^2 per year respectively, and the average values are 188.36, 194.64 and 103.27 kWh/m^2 per year, respectively (Ma et al., 2017).

To calculate the energy consumption of SCC will largely depend on the type and nature of the equipment in the centre which will also be influenced by the square meters of the SCC.

2.8 Cloud System

The cloud system is an essential aspect of autonomous ships that will enable all authorized maritime stakeholders involved to have access to specific information regarding the autonomous ship operations, such as voyage details. This makes the interconnection between ships and ships/shore happen with a cloud system. MASS will communicate via the cloud and share information with other authorized maritime stakeholders. The cloud system is like Apple's iCloud and Windows OneDrive. The cloud system will be like the Danish maritime authority maritime cloud project that was part of the e-Navigation process; it is a technical framework that provides reliable and a stream of seamless electronic information between all authorized maritime stakeholders like ship to ship or ship to shore information streams. The centre of the maritime cloud consists of three core components (Adriaan et al., 2016). The cloud system takes into account IMO's e-navigation as defined as "***the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment***." (IMO, 2006).

According to The American Council for an Energy-Efficient Economy, to save 1GB of data on cloud storage, it consumes 3.1 kWh (Magazine, 2017).

Another study by Carnegie Mellon University was conducted in 2017, the transfer and storage of 1 GB of data consume 7kW/h of energy (C & aş, 2020)

2.9 Port Automation

Port will play a considerable role in Autonomous ships; ports will become smarter and would be able to communicate with the ship to provide real-time arrival and condition information of the MASS. Ports would communicate with autonomous ships to enable docking and optimize unloading, storage and onward delivery via the automated cranes and vehicles at the port (Global Infrastructure Hub, 2021).

Ports will become smart and also leverage on connectivity to store or retrieve data. However, quantifying the amount of data and connectivity with regards to MASS requires an in-depth analysis that this research work will not cover; this is one of the limitations of this research work.

Chapter 3 -Methodology

3.1 Introduction.

To answer the research questions and achieve the research's set objectives, various approaches such as Integrative literature reviews were adopted to analyse the data collected from different literatures. The novelty of this research topic makes it imperative to interpolate and extrapolate data from various sectors to stimulate new thinking about the topic and catalyse further research. The researcher takes account of the maturity of the technology and emerging technologies and the limitations and scope of the research. Finally, Crystal ball is used as a tool using Monte Carlo Simulation model to predict or forecast the impact of MASS on the ICT sector carbon footprint.

3.2 Data Collection.

The data for the research were sourced from secondary sources via literature review, reports, seminars/workshops and credible intergovernmental and governmental organizations databases such as;

- IMO
- EU
- Nigerian Maritime Administration and Safety Agency (NIMASA) and
- other internet sources.

The data collected consist of;

- Energy consumption and carbon footprint
- Conventional ship connectivity
- Autonomous ship connectivity requirement
- The energy requirement for cloud storage
- The energy consumption of cybersecurity and
- Energy consumption of SCC.

3.3 Conventional Ship Connectivity.

Traditionally, conventional ships use AIS signals to avoid a collision at sea. However, these signals from ships are transmitted to the satellite and then to AIS control centre, stored in the cloud. The connectivity and storage involved energy which is largely overlooked. Figure 7 is the model of conventional ship connectivity and transmission of the AIS signal.

3.4 Conventional Ship Connectivity Model

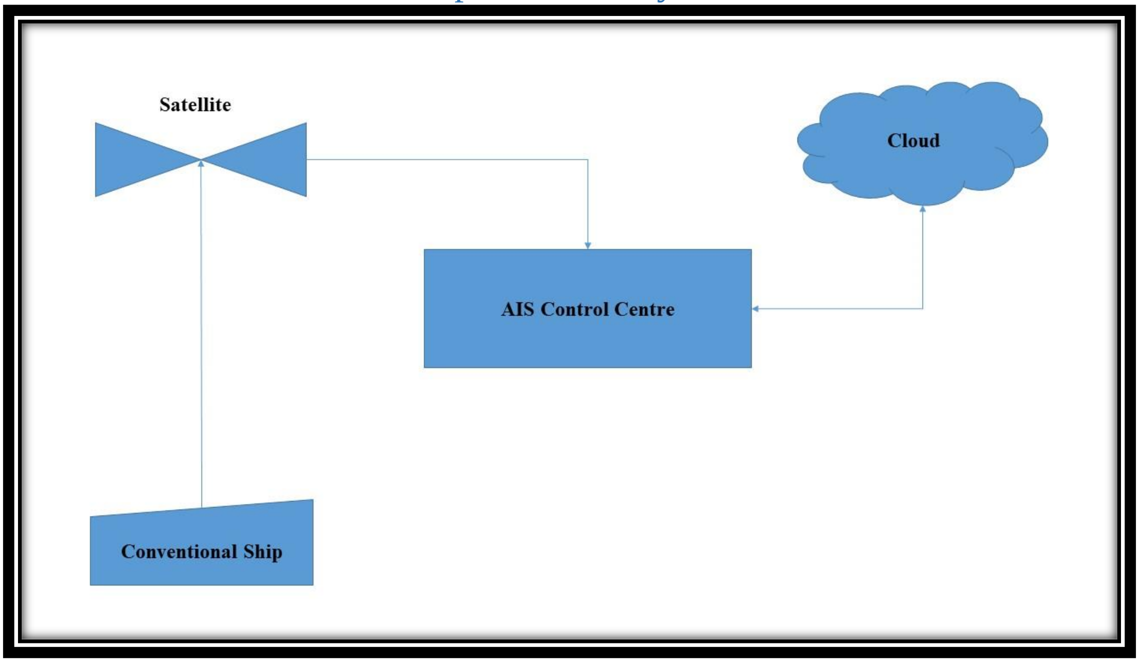

Figure 7. Conventional Ship connectivity and storage model.

In Figure 7, the researcher considers the connectivity between the ship and the AIS satellite and the cloud storage for the AIS data generated.

3.4.1 Proposed Algorithm (Impact of Conventional ship on ICT sector carbon footprint)

The researcher develop a mathematical framework as shown in figure 8, the following are considered;

- ➔ CO2e emitted to generate 1kWh, denoted as (*eK*)
- ➔ Data generated by transmitting AIS signals, denoted as (*d*)
- ➔ kWh required to transmit AIS data from ship to AIS control centre, denoted as (*kT*)
- ➔ CO2e emitted to transmit AIS data control centre, denoted as (*eT*)
- ➔ kWh required to save/store AIS data in the cloud, denoted as (*kD*)
- ➔ CO2e emitted to save/store AIS data in the cloud for, denoted as (*eD)*
- ➔ Time (hour, day, month or year), denoted as (*t*)
- ➔ Conventional Ship carbon footprint, denoted as (*cscfp*)

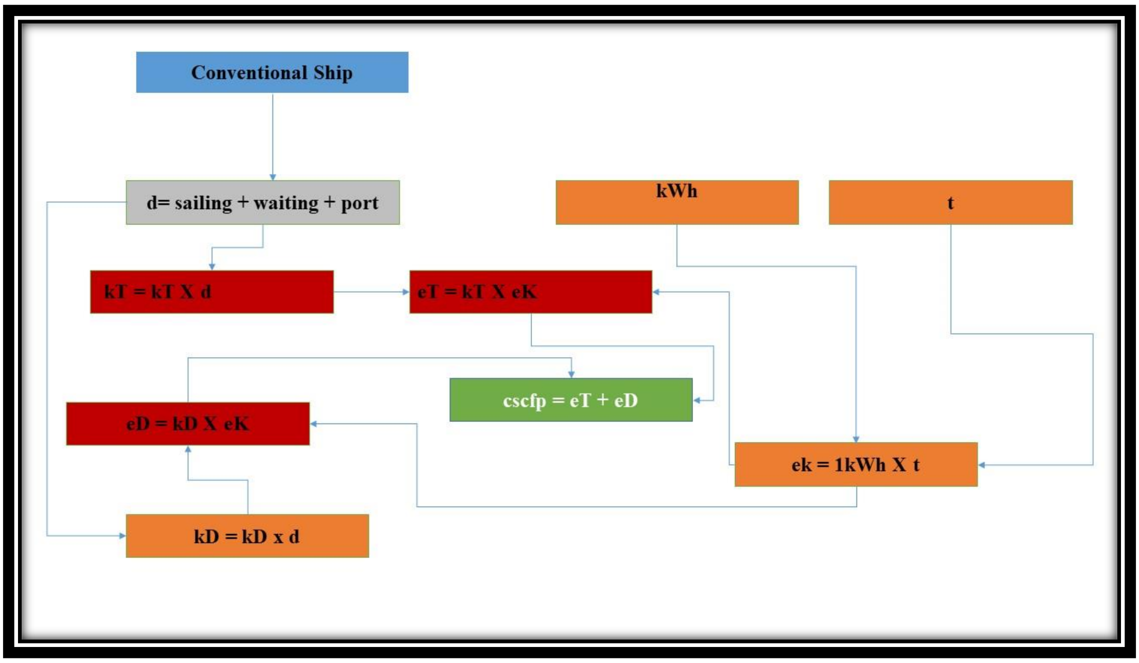

Figure 8. Conventional Ship carbon footprint on ICT sector algorithm.

Figure 9 shows the flowchart on how to calculate the impact of a conventional ship on ICT sector carbon footprint.

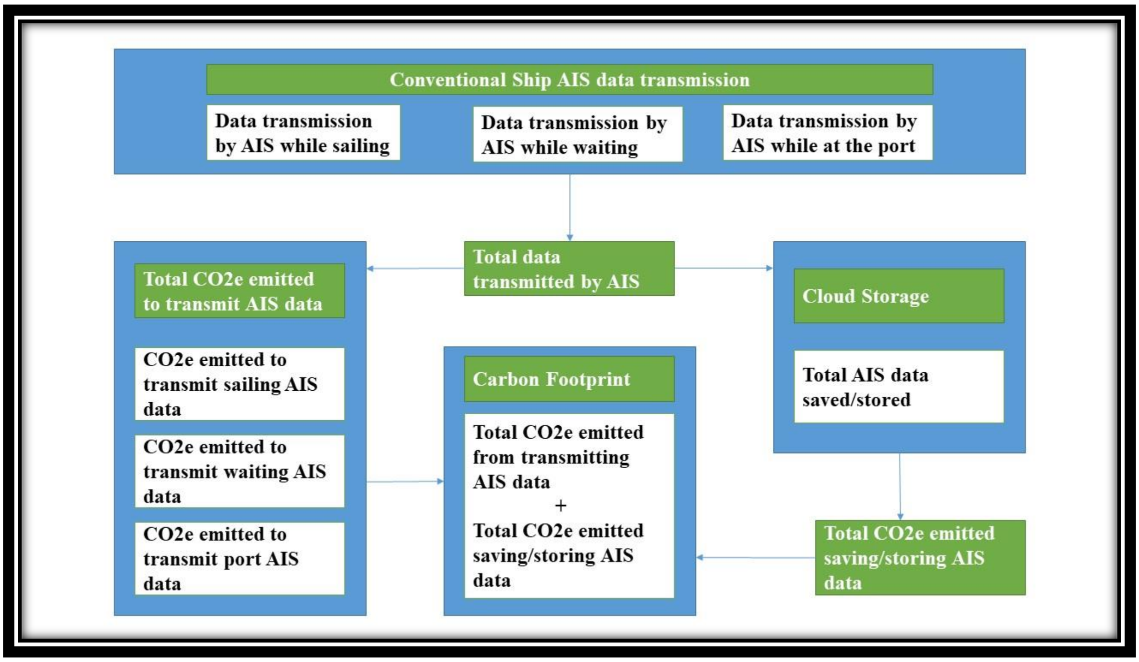

Figure 9. Conventional Ship impact on ICT sector carbon footprint flowchart

3.5 MASS Connectivity Model

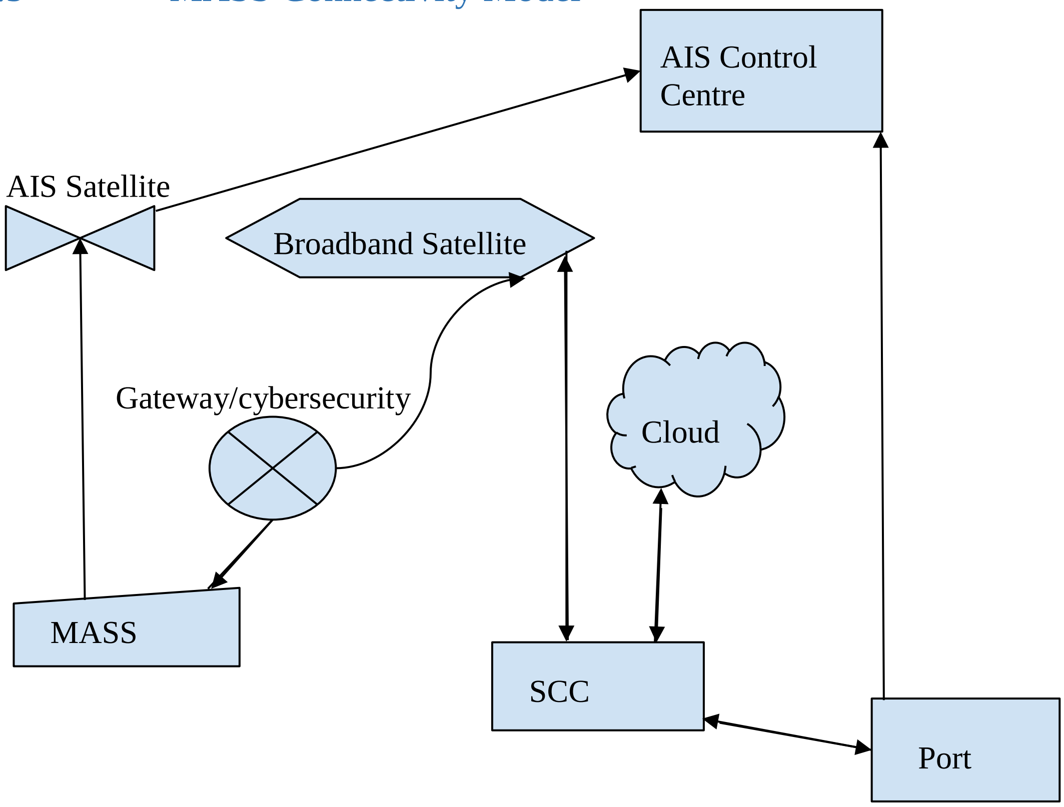

Figure 10. MASS Connectivity Model .

Figure 10 shows a scenario on how MASS interacts with the SCC via ICT infrastructure.

To determine MASS impact on ICT sector carbon footprint, the researcher takes account of the amount of CO2e emitted to provide cybersecurity against cyber-attack and the CO2e SCC will emit to monitor MASS 24/7 in addition to the CO2e emitted to save/store and transmit MASS data. MASS will still use AIS signal to interact with conventional ships in operation hence the CO2e emitted from the AIS signal is considered.

3.5.1 Proposed Algorithm (Impact of MASS on ICT sector carbon footprint)

The researcher developed a mathematical framework to calculate the CO2e emitted by MASS due to using these ICT infrastructures as shown in figure 11.

The mathematical framework is as follows; where *eAIS* represent the total CO2e emitted of the total data transmitted by MASS via AIS, *dM* the total amount of data generated by MASS, *eM* represent the total CO2e emitted to transmit data generated by MASS, *eS* represent the total CO2e emitted as a result of proving cybersecurity to the MASS, *eC* represent the CO2e emitted during storing/saving the data generated by MASS on cloud while *eSC* is the total CO2e emitted as a result of providing power to the SCC 24/7. The impact of MASS carbon footprint on ICT sector is represented by MC.

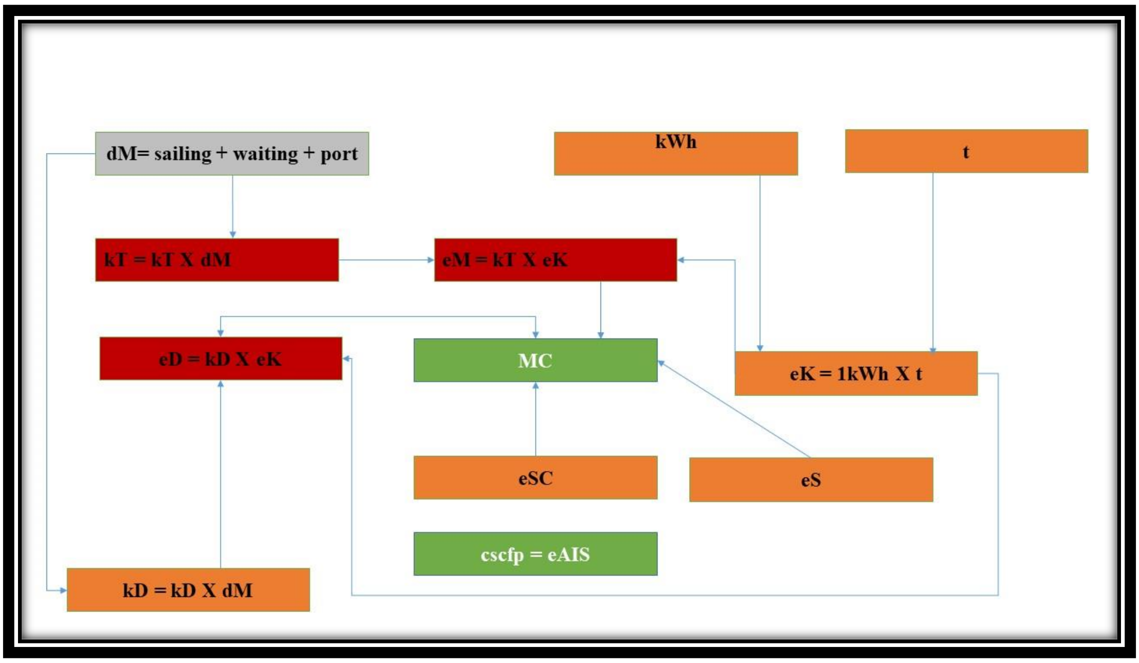

Figure 11. MASS carbon footprint on ICT sector algorithm.

Figure 12 shows the flowchart on how to calculate the impact of MASS on ICT sector carbon footprint.

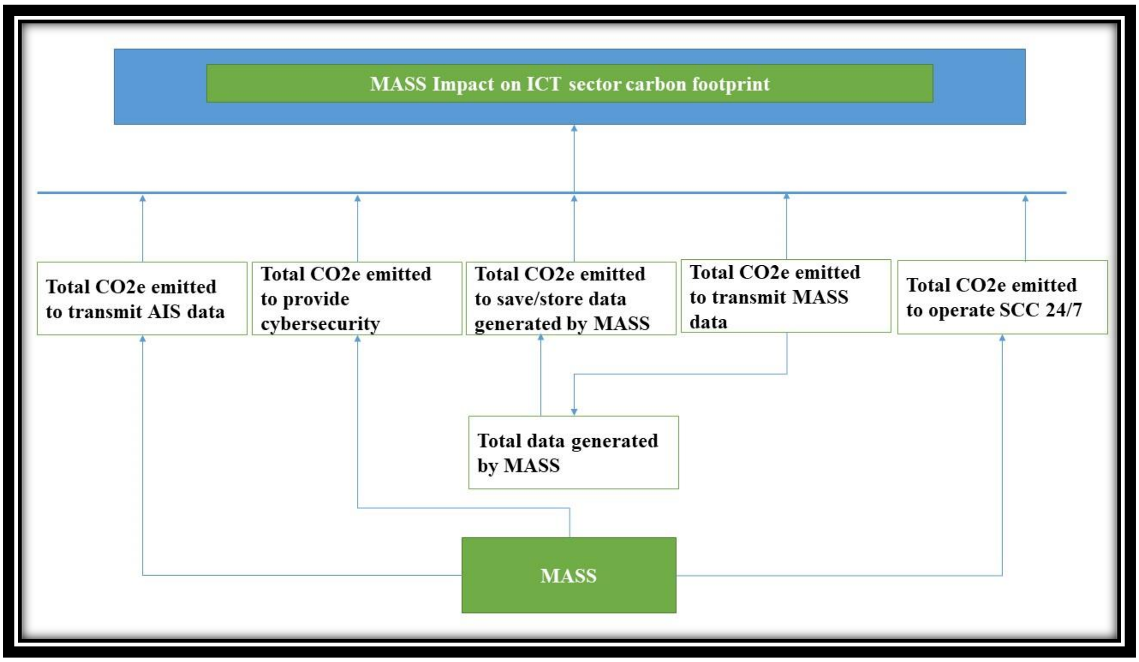

Figure 12. MASS impact on ICT sector carbon footprint flowchart

3.6 Monte Carlos Simulation

The researcher uses Monte Carlo simulations to model the outcome because it cannot be easily predicted due to variations of values from different literatures. Crystal Ball is used to display results in a forecast chart that shows the entire range of possible impact of MASS on the ICT sector carbon footprint.

Chapter 4 -Case Study, Discussion and Scenario (Bulk Carrier, Tanker, Container and MASS)

4.1 Introduction.

This chapter investigates in detail the different types of ships (Bulk Carrier, Tankers, containers) and their impact on the ICT sector's carbon footprint. A model of MASS was designed and critically investigated to analyse the impact on the ICT sector's carbon footprint. The analysis is based on the data generated and connectivity requirements for conventional ships and MASS interacting with ICT infrastructures.

4.2 AIS signals and Data transmission.

AIS signal is broadcasts in every 2 to 10 seconds while underway and every 3 minutes while at anchor. The model shows that when the ship is sailing it will transmit between 360-1800 times while in the port or anchorage/waiting the ship transmit 20 times.

Frequency of AIS transmission(hour)	
360	in every 2-10 seconds while sailing
20	In every 3 minutes while achoring or in port

Table 1. Frequency of AIS signal transmission per hour

AIS signal is 50 bytes of data size; while sailing, it will generate about 432,000 bytes of data and 24,000 bytes of data a day while waiting at anchorage and at the port respectively, as shown in Table 2.

	AIS SIGNAL DATA SIZE	
AIS DATA SIZE PER SINGLE TRANSMISSION	50	bytes
AIS signal transmission data size (Sailing)/hour	18000	bytes
AIS signal transmission data size (Sailing)/day	432000	bytes
AIS signal transmission data size (port)/hour	1000	bytes
AIS signal transmission data size (port)/day	24000	bytes
AIS signal transmission data size(waiting)/hour	1000	bytes
AIS signal transmissiondata size (waiting)/day	24000	bytes
Storage Value	1000000000	byte to GB

Table 2. AIS Signal Data size

4.3 Electricity generation and Emissions.

To generate 1kWh of electricity per hour/day, there will be CO2e, which may vary depending on the country as different countries have different grid mix from different sources of energy, as shown in Table 3.

CO2 Emissions PER HOUR GENERATING ELECTRITY (GLOBAL MIX AVERAGE)			
	gCO2e		
1KW/h	600	Between 60gCO2e to 600gCO2e	
1kw/day	14400		

Table 3. CO2e emitted to generate 1kWh of electricity per hour/day

4.4 Electricity requirement to transmit 1GB of data.

To transmit data via ICT infrastructure it will require electricity to function. Table 4 shows the kWh requirement to transmit 1GB of data over a network infrastructure per hour/day

kW/h REQUIED TO TRANSMIT 1GB OF DATA	
5,14	kW/h
123,36	kW/day

Table 4. kWh required to transmit 1GB of data per hour/day

4.5 Electricity requirement to save/store 1GB of data on cloud.

Cloud storage system runs on electricity, Table 5 shows the kWh requirement to store/save 1GB of data on a cloud system per hour/day.

kW/h TO STORE 1GB ON CLOUD	
3,1	kW/h
74,4	kW/day

Table 5. kWh required to store/save 1GB of data on cloud system per hour/day

4.6 Impact of Conventional Ship on ICT sector carbon footprint

Different type of conventional ships AIS data was collected and analysed using the model developed by the researcher, the following findings was made.

- Bulk Carrier Ship will contribute between 61,666.1kgCO2e/year to 304,035.4kgCO2e/year on the ICT sector carbon footprint.

- ➢ Tanker Ship will contribute between 61,666.1kgCO2e/year to 304,035.4kgCO2e/year on the ICT sector carbon footprint
- ➢ Tanker Ship will contribute between 61,666.1kgCO2e/year to 304,035.4kgCO2e/year to the ICT sector carbon footprint.

4.7 Bulk Carrier Ship Case study

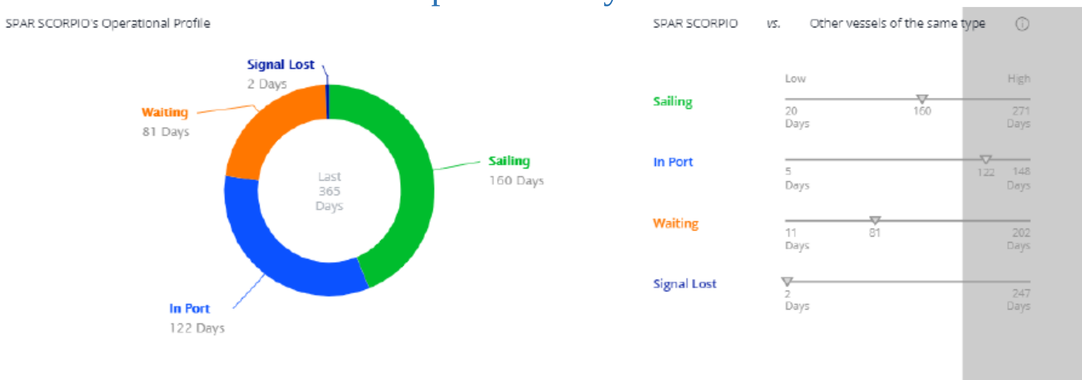

Figure 13. Bulk Carrier activity analysis (NIMASA intelligence system)

Figure 13 shows the breakdown of SPAR SCORPIO operational analysis as compared to other bulk carriers. In the last 365 days, the ship spent 160 days sailing, 81 waiting at anchorage and 122 days in port. Within the same 365 days, another bulk carrier spent 271 days sailing, while the low is 20 days.

Using Oracle Crystal Ball Monte Carlo simulation software, the researcher estimated the impact of SPAR SCORPIO on the ICT sector.

CONVENTINAL SHIP TRANSMMION RECORDS			
Sailing	=	160	days
Port	=	81	days
waiting	=	122	days

SIZE OF DATA GENERATED		
Sailling	0,06912	Gigabytes
Port	0,001944	Gigabytes
Waiting	0,002928	Gigabytes
Total data Size	0,073992	Gigabytes

Table 6. SPAR SCORPIO AIS transmission signal data

As shown in Table 6, SPAR SCORPIO generated **0.073992** Gigabytes of data while transmitting AIS signals from the ship to the AIS control centre.

Using the formula; *d = sailing + waiting + port*

$$d = 0.06912 + 0.001944 + 0.002928 = \mathbf{0.073992\ GB/year.}$$

To calculate the carbon footprint of SPAR SCORPIO on the ICT sector, the researcher calculate the CO2e emitted to transmit of Data from ship to AIS control centre using the formula

$$Sailing\ (d) = (0.06912\ X\ eT(160days))\ where\ eT = \mathbf{1,776,384/\ day}$$

$$= 0.06912\ X\ (1776384\ X\ 160)$$

$$Sailing\ (d) = \mathbf{44570469.34\ gCO2e/year}$$

$$Port\ (d) = (0.001944\ X\ eT\ (81\ days))$$

$$= 0.001944\ X\ (1776384\ X\ 81)$$

$$Port\ (d) = \mathbf{3453.290496\ gCO2e/year}$$

$$waiting\ (d) = 0.002928\ X\ eT\ (122\ days)$$

$$= 0.002928\ X\ (1776384\ X\ 122)$$

$$= \mathbf{634552.787\ gCO2e/year}$$

The CO2e to transmit AIS signal for SPAR SCORPIO in 365 days is;

$$= 44570469.34 + 3453.290496 + 634552.787$$

$$\sum(d\ X\ eT) = \mathbf{44,579,123.88\ gCO2e/year}$$

CO2 EMISSIONS TO TRANSMIT AIS DATA			
Sailling	0,06912	44570469,34	
Port	0,001944	3453,290496	
Waiting	0,002928	5201,252352	
Total	**44579123,88**		**Total gCO2e via AIS data transmission/year**

Table 7. 365 days CO2e of SPAR SCORPIO transmitting AIS signal

The researcher also calculate the CO2e emitted to store/save SPAR SCORPIO's AIS data on the cloud for 365 days using the formula as shown on table 7;

$$eD = d\ X\ eD;\ where\ eD\ is\ 385689600\ gCO2e\ to\ store/save\ 1GB\ of\ data$$

$$= 0.073992\ X\ 385689600$$

$$eD = 28537944.9\ gCO2e/year$$

CO2 EMISSIONS STORING AIS DATA ON CLOUD	
28537944.9	Total gCO_2e storing AIS data/year

Table 8. CO2e to store/save SPAR SCORPIO's AIS data on cloud system

The carbon footprint of SPAR SCORPIO is;

$$cscfp = \sum(d\ X\ eT) + eD)$$

= ***44579123.88 gCO2e/year + 28537944.9 gCO2e/year***

cscfp ***= 73,117,068.76 gCO2e/year***

= 73,117.1 kgCO2e/year

CSCFP	73117068,76	gCO_2e/year
	73117,1	$kgCO_2e$/year

Table 9. SPAR SCORPIO's carbon footprint

The research also forecasted the carbon footprint of SPAR SCORPIO lifespan on ICT sector

lcscfp = cscfp X 25years

= 73,117.1 X 25

lcscfp = ***1,827,926.719 kgCO2e/year***

= 1,827.927 mtCO2e/25years

4.7.1 Monte Carlo simulation using Crystal Ball analysis (Bulk Carrier)

The researcher used Monte Carlo simulation software to determine the possible implications of a conventional ship impact on the ICT sector carbon footprint with some degree of certainty; Figure 14 is the analysis of SPAR SCORPIO (Bulk Carrier).

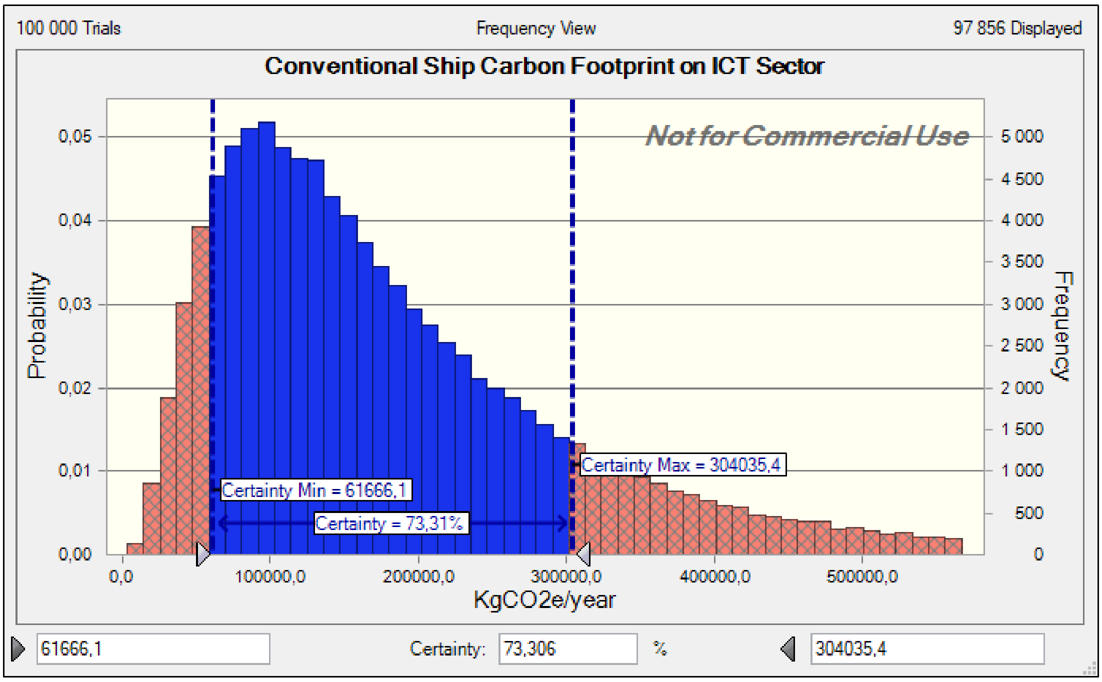

Figure 14. Conventional ship carbon footprint on ICT sector (SPAR SCORPIO)

As shown in figure 14, the researcher simulates the impact using 100,000 trials to analyse the carbon footprint implications; at 73.31% certainty, SPAR SCORPIO will contribute between 61,666.1kgCO2e/year to 304,035.4kgCO2e/year. This shows the possible impact that SPAR SCORPIO contributed to the growing CO2e of the ICT sector.

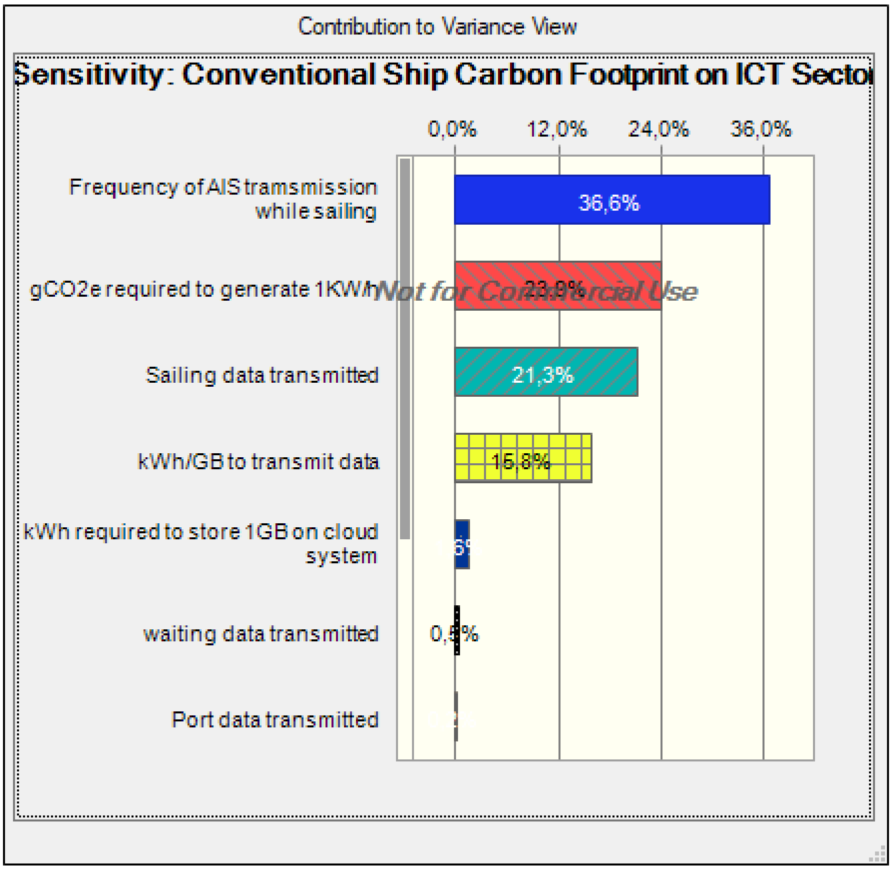

Figure 15. Sensitivity analysis of Conventional ship ICT carbon footprint (Spar Scorpio)

The sensitivity analysis in figure 15, shows the different variables that affect the carbon footprint; the frequency of data transmission while sailing positively affects the carbon footprint by 36.6%. The amount of CO2e emitted to generate 1kWh of electricity affects the carbon footprint by 23.9%. Data transmitted while sailing affects the carbon footprint by 21.3%. The amount of kWh needed to transmit 1GB of data impacts the carbon footprint by 15.8%, the amount of kWh needed to store/save 1GB of data also affects the carbon footprint by 6%, while waiting data and port data transmitted affects the carbon footprints by 0.5 and 0.2 respectively. This shows that the rate at which the AIS is transmitting signals while sailing contributes a large percentage of what affects the carbon footprint as each signal is 50 bytes of data.

See Appendix A and B for Tanker and Container ship.

4.8 Scenario(s)

The scenario will help in making prediction on the possible impact of MASS on the ICT sector's carbon footprint using reasonable assumptions. The research makes three

(3) different scenario with different variables to investigate the possible impact of MASS on the ICT sector.

4.8.1 Scenario (1) MASS Carbon Footprint

The researcher calculate the carbon footprint of MASS on the ICT carbon sector with the following assumptions:

- Sailing for 300 days
- Waiting in port for 60 days
- Waiting at anchorage 5 days
- Minimum of 4TB/day data generated by the MASS
- Using emission equivalent of 1bitcoin transaction to provide cybersecurity for MASS
- Using kWh/m2 of non-residential building equivalent to provide electricity to SSC and the equipment building

The analysis shows that MASS will contribute between 6,998,187,655.06mtCO2e/year to 35,594,154,581.97mtCO2e/year on the ICT sector carbon footprint.

The results obtained show that the annual data generated by MASS, the amount of CO2e emitted to generate 1kWh of electricity, and the amount of kWh needed to store/save the data generated by MASS are the variables that largely contribute to ICT sector carbon.

See Appendix C for detailed information.

4.8.2 Scenario (2)

Today electricity is mainly produced using fossil energy which has high CO2e during the process; however, Sweden's mix is (0.06 kg CO2e/kWh) with a relatively low GHG-emitting electricity. According to the Swedish Government, 56% of the total electricity generated in Sweden in 2019 comes from renewable energy; which is the highest in the EU (Institute, 2020).

The researcher made the following assumption taking into consideration of renewable energy as a major source of electricity.

Main assumptions;

- Source of electricity 80% renewable with the total of 10gCO2e kWh
- Sailing for 300 days

- Waiting in port for 60 days
- Waiting at anchorage 5 days
- Minimum of 4TB/day data generated by the MASS
- Using emission equivalent of 1bitcoin transaction to provide cybersecurity for MASS
- Using kWh/m2 of non-residential building equivalent to provide electricity to SSC and the equipment building

Figure 16 shows the result on how MASS will contribute between 32,496,043.13mtCO2e/year to 488,220,617.80mtCO2e/year to the ICT sector carbon footprint with 80% renewable source of energy.

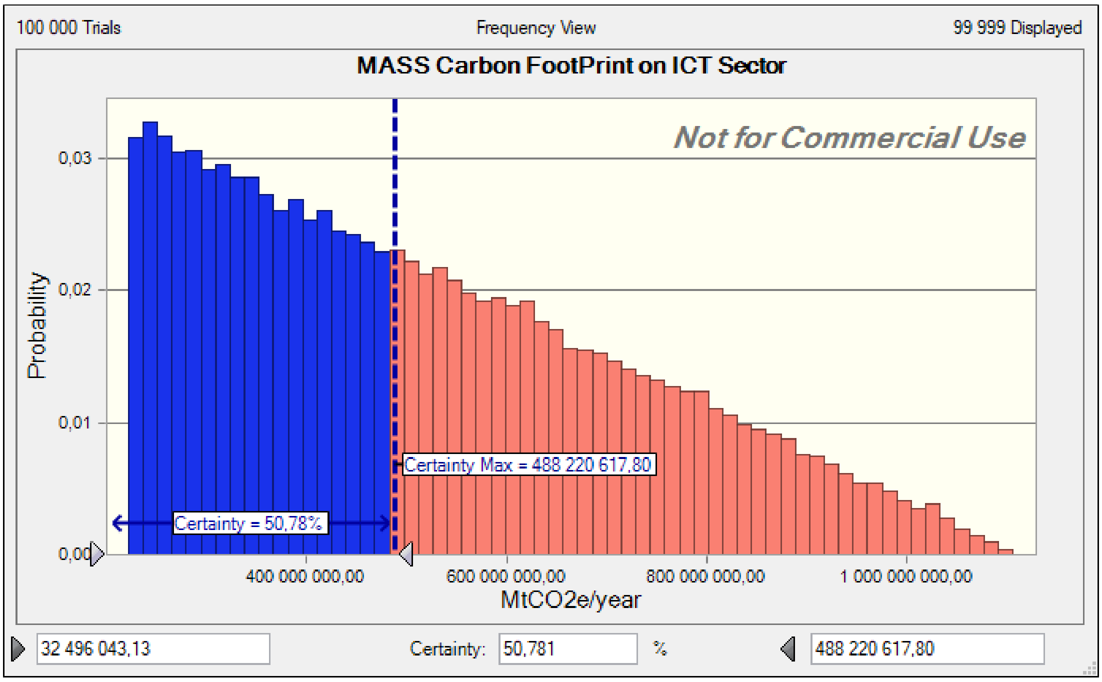

Figure 16. MASS impact on ICT sector carbon footprint (scenario 1)

Figure 17 shows the sensitivity analysis how annual data generated greatly affect the impact of MASS on the ICT sector. This scenario shows that 80% renewable energy to generate electricity will not completely decarbonized MASS impact on the ICT sector carbon footprint, as it was also found out that the data generated by MASS is a major concern.

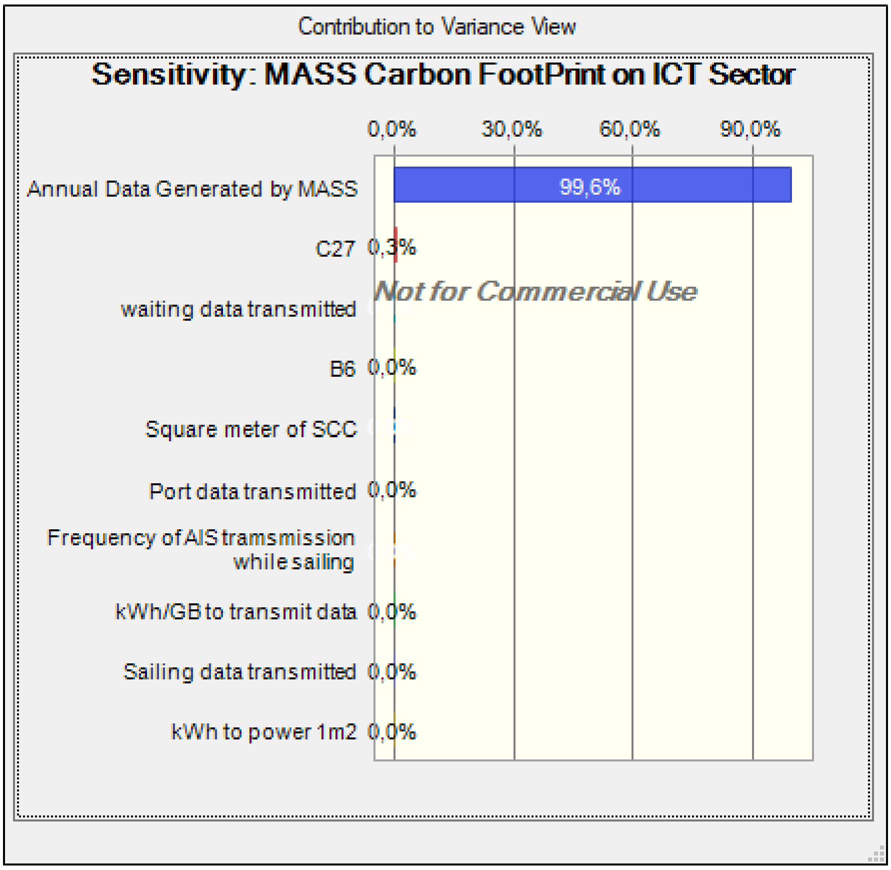

Figure 17. MASS sensitivity analysis (scenario 1)

4.8.3 Scenario (3) MASS 2040

The maritime industry is in the process of transformation towards electrification, digitization, interconnection, cloud computing, and big data. However, many countries have yet to develop a long-term framework for the automation of the maritime sector. According to DNV GL Energy Transition Outlook (2018), the schedule of Maritime Autonomous Surface Ships (MASS) Working and Correspondence groups at IMO, international regulations for autonomous ships are projected to be in place before 2035. But for detailed operations in national waters, inland or near-coastal waters, it is foreseen that autonomous ships may be navigating the waters by 2028 (World Maritime University, 2018)

Taken into consideration of the power sector; there is no single vision for how the global energy industry will develop in the future, one fact is clear; the industry is on the cusp of tremendous changes. How energy companies respond will depend on their operating locations, regulatory environment, asset portfolio structure, changing customer needs, economic maturity, and the level of technology adoption required (Deloitte Energy, 2021).

For example, the proportion of renewable energy used in Sweden continues to grow. Already in 2012, the country reached the government's 2020 target of 50%. The goal of the electricity sector is to produce 100% renewable electricity by 2040 (Swedish Institute, 2015). This projection shows that operating MASS in Sweden by 2040 will have zero effect on the ICT sector's carbon footprint.

Communication, network, and data processing equipment are the main components that use high energy for their operation. So it's time to choose green, energy-efficient equipment for communications, network, and data processing. Video surveillance communications, cluster networks, and other fields of application need to expend a lot of energy to complete their work. Similarly, to increase secure communications it spends considerable power on encryption and decryption processing (Adimoolam et al., 2020).

The researcher calculate the carbon footprint of MASS on the ICT carbon sector in the second scenario with the following assumptions:

- Sailing for 300 days
- Waiting in port for 60 days
- Waiting at anchorage 5 days
- Minimum of 1GB/hour data generated by the MASS
- 0gCO2e-10gCO2e to generate 1kWh
- 1kWh-2kWh to transmit 1GB
- 1kWh-2kWh to save/store 1GB of data on cloud.
- Using emission equivalent of 1bitcoin transaction to provide cybersecurity for MASS
- Using kWh/m2 of non-residential building equivalent to provide electricity to SSC and the equipment building

Figure 18 shows that in 2040 MASS will contribute between 7,000mtCO2e/year to 14,600mtCO2e/year to the ICT sector carbon footprint with 48% certainty level.

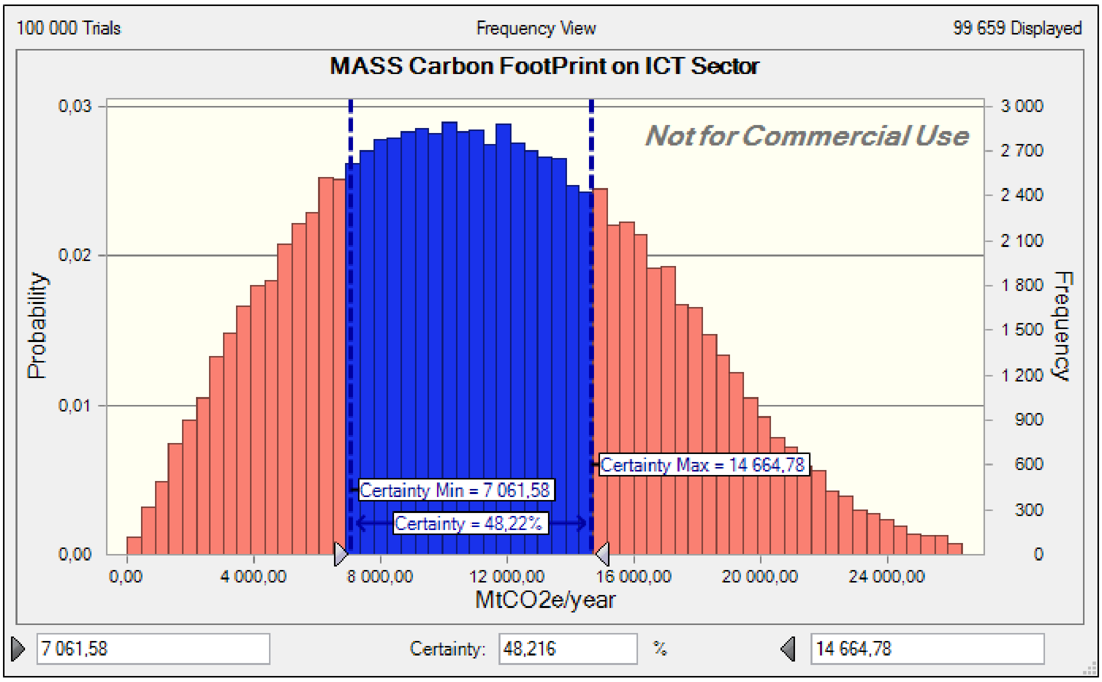

Figure 18. MASS impact on ICT sector carbon footprint (scenario 2)

Figure 19 shows the sensitivity analysis how the gCO2e generated to produce 1kWh of electricity affect the Impact of MASS on the ICT sector carbon footprint by 59.8% while kWh required to save/store 1GB on cloud affect the impact of MASS on the ICT sector by 29.3% .

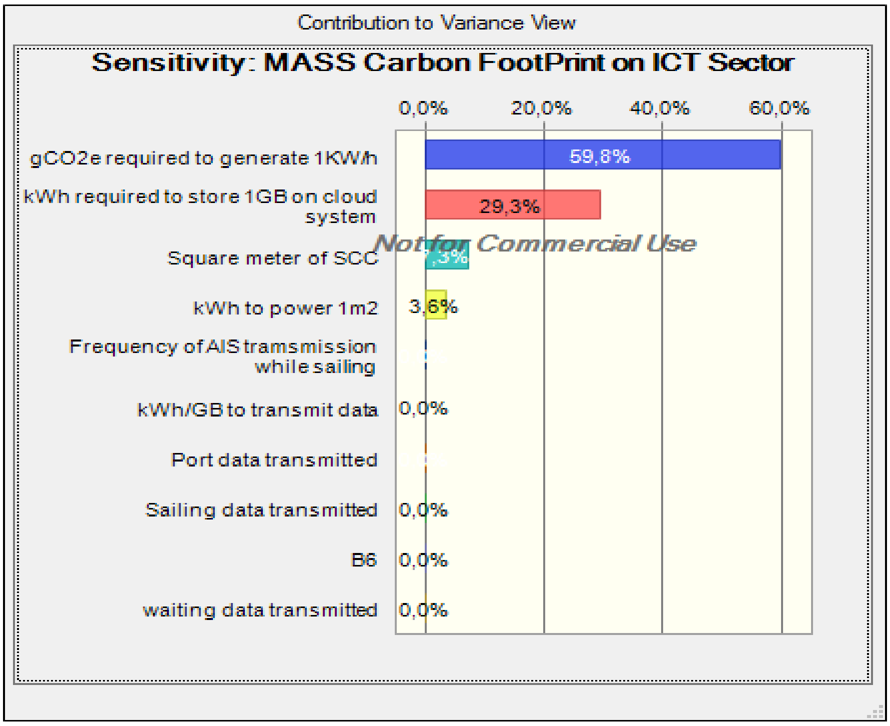

Figure 19. MASS sensitivity analysis (scenario 2)

4.9 Findings

Statistics on figure 20 show that CO2e from international shipping according to 2020 estimates, by ship type. Bulk carriers emitted 440 million metric tons of CO2 on average, while container ships emitted 140 million metric tons of CO2 per year. (Ian Tiseo, 2021).

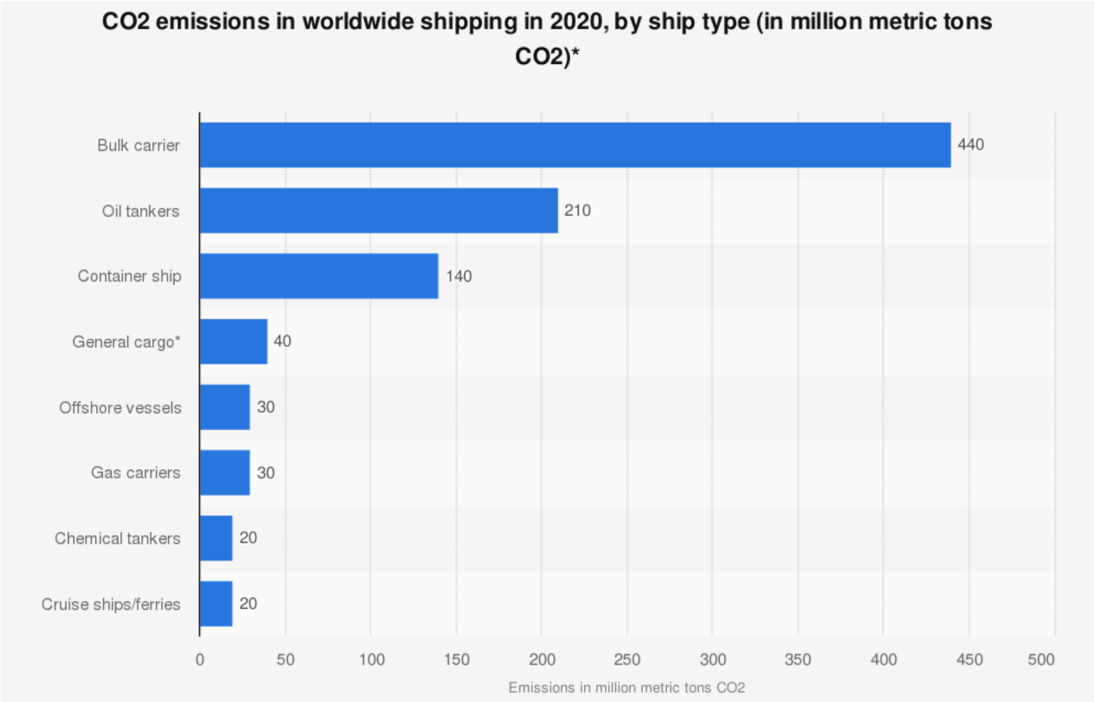

Figure 2013. CO2 emissions in worldwide shipping in 2020 by ship type (Ian Tiseo, 2021)

The global merchant fleet had a capacity of 74,505 ships, according to BIMCO ICS Seafarer Workforce Report 2021, at the start of 2021. In the baseline scenario, the total fleet is projected to reach 79,282 by the end of 2025 (Sand, 2021). This indicates that 79,282 ships are responsible for the current international shipping CO2e. Even if the fleet size grows at 6% rate annually, MASS can help meet the IMO's 2050 target.

Using Monte Carlo simulations, the researcher calculates the impact of various ship types and MASS on the ICT carbon footprint. The results of the findings show that all the conventional ship types have little or negligible impact on the ICT sector carbon footprint; However, the analysis shows that the frequencies of AIS signals in transmitting data, the amount of CO2e emitted to generate electricity influenced the amount of impact of conventional ship on the ICT sector carbon footprint. On the other hand, MASS can impact the ICT sector carbon footprint significantly with the current technology available in the ICT sector. The analysis shows that the major contributor is the amount of data MASS generates annually, followed by the CO2e emitted to generate electricity for the infrastructures and the amount of electricity required to store/save the data on the cloud.

The researcher in the first scenario, applied 80% renewable energy as a source of electricity to investigate the impact of MASS on the ICT sector; the result shows a drop of the impact of MASS on the ICT sector but even with renewable energy as the major source of the electricity MASS will still contribute to CO2e to the ICT sector to a large degree.

According to Nguyen (2020), MASS has the potential of 5%-10% energy efficiency as compared to a conventional ship, in order to meet the IMO’s 2050 target of eliminating air emissions for the shipping industry, alternative or electric energy must be used. However, IMO’s 2050 can be achieved with MASS using alternative or electric energy but the CO2e will be shifted to the ICT sector.

The future of MASS in 2040 and the maritime industry to meet the IMO’s 2050 target and Paris Agreement ambition largely depends on low energy smart ICT devices, optimized data and use of renewable energy.

Chapter 5 -Conclusion and Future Research

5.1 Conclusion

The focal point of this study is to provide an insight into how MASS will impact the ICT sector carbon footprint. In order to fulfil the objectives of the study, the research focused mainly on;

- The ICT infrastructures needed to support the operation of MASS, taking into account the data generated and CO2e emitted to transmit the data MASS generated during operation
- Energy requirement and CO2e emitted to save/store the data MASS generated during operation.
- The energy requirement and CO2e to provide cybersecurity and the energy requirement to operate SCC.

The research work did not cover the ICT devices life cycle, port and terminals.

The novelty of the research informs the use of a mathematical model to develop a framework using data from literature review and other sources to model the impact of MASS on the ICT sector carbon footprint. In addition, the study also analyses the impact of a conventional ship of different types on the ICT sector carbon footprint.

The findings show that conventional ships have little impact on the CO2e on the ICT sector carbon footprint. Different scenarios were simulated, and it was revealed that that MASS would significantly impact the growing ICT CO2e with the current ICT infrastructure. Another scenario shows that 80% of renewable energy as the source of electricity will significantly reduce the MASS impact on the ICT sector carbon footprint but not enough to make the desired reduction without the ICT sector evolving to optimize the data size MASS generate during operation.

The future of MASS in 2040 shows a positive impact in the reduction of the impact of MASS on the ICT sector carbon footprint that will help meet the IMO's 2050 target with the current trend and technology evaluation and the use of renewable energy in both the ICT and power sectors to generate electricity.

5.2 Future Research

The future of MASS is covered with many uncertainties. The maturity and trend of technological advancements show that not only MASS but ports, terminals and other facilities that will interface with MASS will become smarter. ICT infrastructures will become the primary driver for the realization of MASS; understanding the energy requirements to power the ICT infrastructures to support the operation of MASS is crucial in measuring the CO2e impact of MASS on the ICT sector carbon footprint.

Future studies will investigate the smart components at the port and the SCC equipment that will support the operation of MASS. The detailed power consumption of the ICT infrastructure will also be studied to see the full scale of the CO2e impact on the ICT sector carbon footprint.

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Appendix

Appendix A Tanker Ship

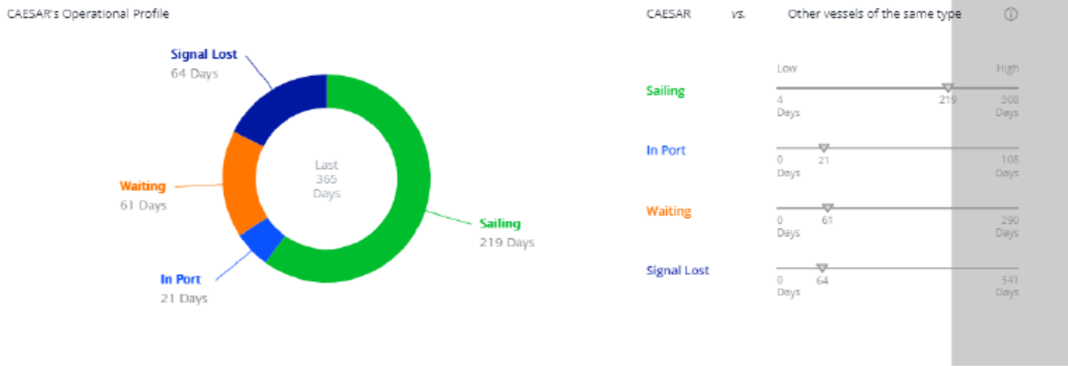

Figure 141.Tanker activity analysis (NIMASA intelligence system)

Figure 21 shows the breakdown of CAESAR operational analysis as compared to other tankers. In the last 365 days the ship spent 219 days sailing, 61 days waiting at anchorage and 21 days in port. Within the same 365 days another tanker spent 306 days sailing while low is 4 days.

Using Oracle Crystal Ball Monte Carlo simulation software the researcher estimated the impact of CAESAR on the ICT sector.

CONVENTINAL SHIP TRANSMMION RECORDS			
Sailing	=	219	days
Port	=	61	days
waiting	=	21	days

SIZE OF DATA GENERATED		
Sailling	0,094608	Gigabytes
Port	0,001464	Gigabytes
Waiting	0,000504	Gigabytes
Total data Size	0,096576	**Gigabytes**

Table 10. CAESAR AIS transmission signal data

As shown in table 10, CAESAR generated **0.096576** Gigabytes of data while transmitting AIS signals from the ship to the AIS control centre.

Using the formula; $d = sailing + waiting + port$

$$d = 0.094608 + 0.001464 + 0.000504 = \mathbf{0.096576\ GB/year}$$

To calculate the carbon footprint of CAESAR on the ICT sector, the researcher calculate the CO_2e emitted to transmit of Data from ship to AIS Control Centre using the formula

$$Sailing\ (d) = (0.094608\ X\ eT(219days))\ where\ eT = \mathbf{1{,}776{,}384gCO_2e/\ day}$$

$$= 0.094608\ X\ (1776384\ X\ 219)$$

$$Sailing\ (d) = \mathbf{50586101.38\ gCO_2e/year}$$

$$Port\ (d) = (0.001464\ X\ eT\ (61\ days))$$

$$= 0.001464\ X\ (1776384\ X\ 61)$$

$$Port\ (d) = \mathbf{2600.626176\ gCO_2e/year}$$

$$waiting\ (d) = 0.000504\ X\ eT\ (21\ days)$$

$$= 0.000504\ X\ (1776384\ X\ 21)$$

$$= \mathbf{0.000504\ gCO_2e/year}$$

The CO_2e to transmit AIS signal for SPAR SCORPIO in 365 days is;

$$= 50586101.38 + 2600.626176 + 0.000504$$

$$\sum(d\ X\ eT) = \mathbf{50589597.3\ gCO_2e/year}$$

CO2 EMISSIONS TO TRANSMIT AIS DATA			
Sailling	0,094608	50586101,38	
Port	0,001464	2600,626176	
Waiting	0,000504	895,297536	
Total	**50589597,3**		**Total gCO2e via AIS data transmission/year**

Table 11. 365 days CO2e of CAESAR transmitting AIS signal

The researcher also calculate the CO_2e emitted to store/save CAESAR's AIS data on the cloud for 365 days using the formula;

$$eD = d\ X\ eD;\ where\ eD\ is\ 385689600\ gCO_2e\ to\ store/save\ 1GB\ of\ data$$

$$= 0.096576\ X\ 385689600$$

$$\mathbf{eD = 37248358.8\ gCO_2e/year}$$

CO2 EMISSIONS STORING AIS DATA ON CLOUD	
37248358,8	**Total gCO2e storing AIS data/year**

Table 12. CO2e to store/save CAESAR's AIS data on cloud system

The carbon footprint of CAESAR is;

$$cscfp = \sum(d\ X\ eT)\ +\ (eD)$$

= 50589597.3 gCO2e/year + 37248358.8 gCO2e/year

cscfp = ***8783956.11gCO2e/year***

= 87838.0kgCO2e/year

CSCFP	87837956,11	gCO2e/year
	87838,0	kgCO2e/year

Table 13. CAESAR's carbon footprint

The research also forecasted the carbon footprint of the conventional ship lifespan on ICT sector

lcscfp = cscfp X 25years

= 87838.0 X 25

lcscfp = ***2195948.9 kgCO2e/year***

= 2,195.95 mtCO2e/25years

Monte Carlo simulation using Crystal Ball analysis (Tanker)

The impact of CAESAR (Tanker) on the ICT sector carbon footprint with 73.556 degree of certainty is shown in Figure 22.

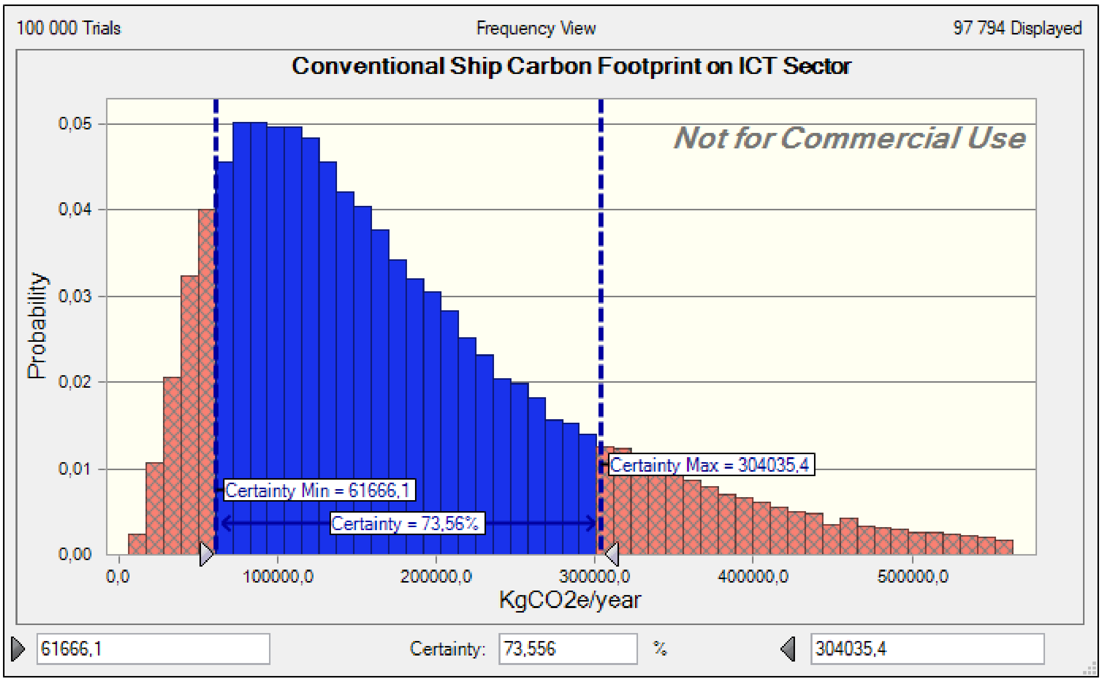

Figure 22. Conventional ship carbon footprint on ICT sector (CAESAR)

In figure 22, the researcher simulates the impact using 100,000 trials to analyses the carbon footprint implications, at 73.31% certainty, CAESAR will contribute between

61,666.1kgCO2e/year to 304,035.4kgCO2e/year. This shows the possible impact that CAESAR contributed to the growing CO2e of the ICT sector.

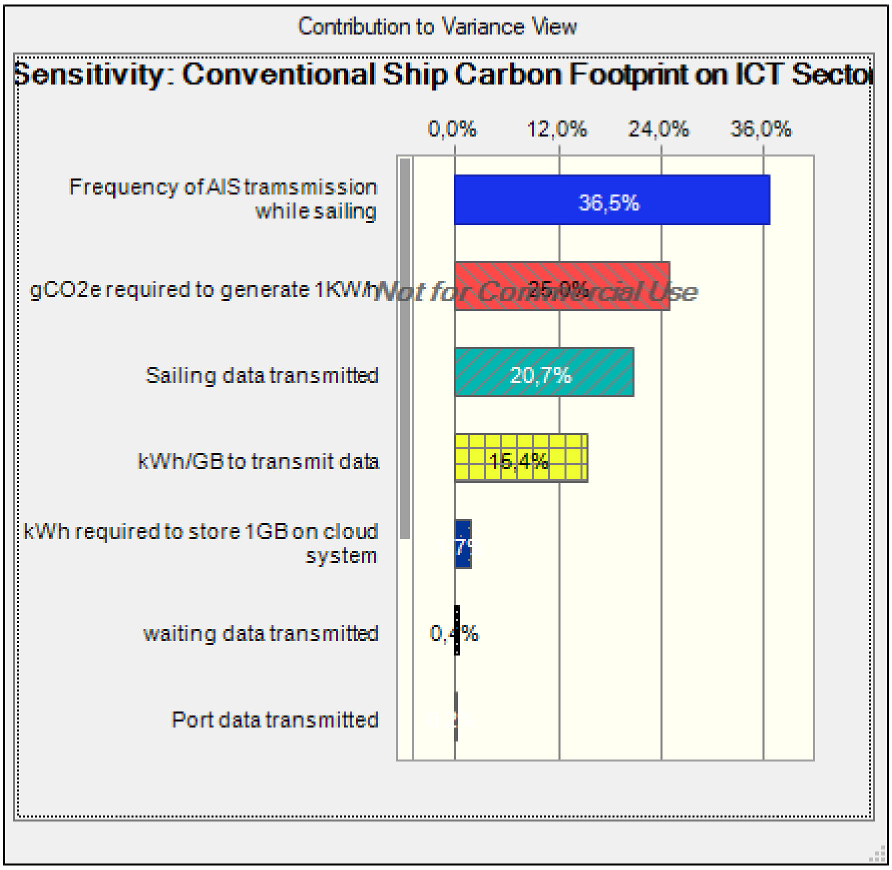

Figure 153. Sensitivity analysis of Conventional ship ICT carbon footprint (CAESAR)

In Figure 23, the sensitivity analysis shows the different variables that affect the carbon footprint; the frequency of transmission while sailing positively affects the carbon footprint by 36.5%, the amount of CO2e emitted to generate 1kWh of electricity affects the carbon footprint by 25.0%. Sailing data transmitted affects the carbon footprint by 20.7%, the amount of kWh needed to transmit 1GB of data impacts the carbon footprint by 15.4%, the amount of kWh needed to store/save 1GB of data also affects the carbon footprint by 7% while waiting data and port data transmitted affects the carbon footprints by 0.4 and 0.1 respectively. This shows that the rate at which the AIS is transmitting signals while sailing contribute the large percentage of what affects the carbon footprint as each signal is 50 bytes of data.

Appendix B Container Ship

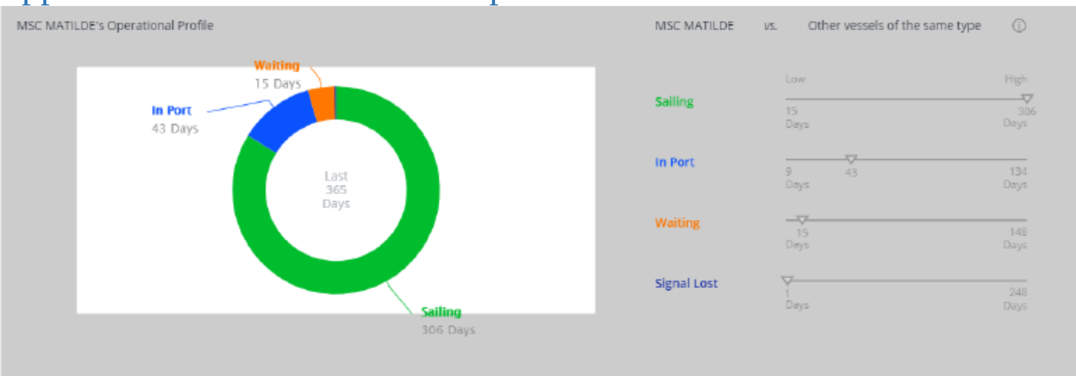

Figure 164. Container activity analysis (NIMASA intelligence system)

Figure 24 shows the breakdown of MSC MATILDE operational analysis as compared to other tankers. In the last 365 days the ship spent 306 days sailing, 15 days waiting at anchorage and 43 days in port. This shows that MSC MATILDE spent the highest number of days sailing among other Containers.

Using Oracle Crystal Ball Monte Carlo simulation software the researcher estimated the impact of MSC MATILDE on the ICT sector.

CONVENTINAL SHIP TRANSMMION RECORDS			
Sailing	=	306	days
Port	=	43	days
waiting	=	15	days

SIZE OF DATA GENERATED		
Sailling	0,132192	Gigabytes
Port	0,001032	Gigabytes
Waiting	0,00036	Gigabytes
Total data Size	0,133584	**Gigabytes**

Table 14. MSC MATILDE AIS transmission signal data

As shown in table 14, MSC MATILDE generated **0.133584** Gigabytes of data while transmitting AIS signals from the ship to the AIS Control Centre.

Using the formula; $d = sailing + waiting + port$

$$d = 0.132192 + 0.001032 + 0.00036 = \mathbf{0.133584\ GB/year}$$

To calculate the carbon footprint of MSC MATILDE on the ICT sector, the researcher calculate the CO_2e emitted to transmit of Data from ship to AIS control centre using the formula

$$\text{Sailing } (d) = (0.132192 \text{ X } eT(306\text{days})) \text{ where } eT = \mathbf{1{,}776{,}384 gCO_2e/ day}$$

$$= 0.132192 \text{ X } (1776384 \text{ X } 306)$$

$$\text{Sailing } (d) = \mathbf{85475846.36 \ gCO_2e/year}$$

$$\text{Port } (d) = (0.0001032 \text{ X } eT \ (43 \text{ days}))$$

$$= 0.0001032 \text{ X } (1776384 \text{ X } 43)$$

$$\text{Port } (d) = \mathbf{1833.228288 \ gCO_2e/year}$$

$$\text{waiting } (d) = 0.000504 \text{ X } eT \ (15 \text{ days})$$

$$= 0.000504 \text{ X } (1776384 \text{ X } 15)$$

$$= \mathbf{639.49824 \ gCO_2e/year}$$

The CO_2e to transmit AIS signal for MSC MATILDE in 365 days is;

$$= 85475846.36 + 1833.228288 + 639.49824$$

$$\sum(d \text{ X } eT) = \mathbf{85478319.08 \ gCO_2e/year}$$

CO2 EMISSIONS TO TRANSMIT AIS DATA			
Sailling	0,132192	85475846,36	
Port	0,001032	1833,228288	
Waiting	0,00036	639,49824	
Total	**85478319,08**		**Total gCO₂e via AIS data transmission/year**

Table 15. 365 days CO2e of MSC MATILDE transmitting AIS signal

The researcher also calculate the CO_2e emitted to store/save MSC MATILDE's AIS data on the cloud for 365 days using the formula;

eD = d X eD; where eD is 385689600 gCO2e to store/save 1GB of data

$$= 0.133584 \text{ X } 385689600$$

$$\mathbf{eD = 51521959.5 \ gCO_2e/year}$$

CO2 EMISSIONS STORING AIS DATA ON CLOUD	
51521959,5	Total gCO₂e storing AIS data/year

Table 16. CO2e to store/save MSC MATILDE's AIS data on cloud system

The carbon footprint of MSC MATILDE is;

$$cscfp = \sum(d\ X\ eT) + (eD)$$

$$= \mathbf{85478319.08\ gCO2e/year + 51521959.5\ gCO2e/year}$$

$$cscfp = \mathbf{137000278.6gCO2e/year}$$

$$= \mathbf{137000.3kgCO2e/year}$$

CSCFP	137000278,6	**gCO$_2$e/year**
	137000,3	**kgCO$_2$e/year**

Table 17. MSC MATILDE's carbon footprint

The research also forecast the carbon footprint of the conventional ship lifespan on ICT sector

$$lcscfp = cscfp\ X\ 25years$$

$$= 137000.3\ X\ 25$$

$$lcscfp = \mathbf{3425007.0\ kgCO2e/year}$$

$$= \mathbf{3,425.007\ mtCO2e/25years}$$

Monte Carlo simulation using Crystal Ball analysis (Container)

The impact of MSC MATILDE (Container) on the ICT sector carbon footprint with 73.574 degree of certainty is shown in Figure 25

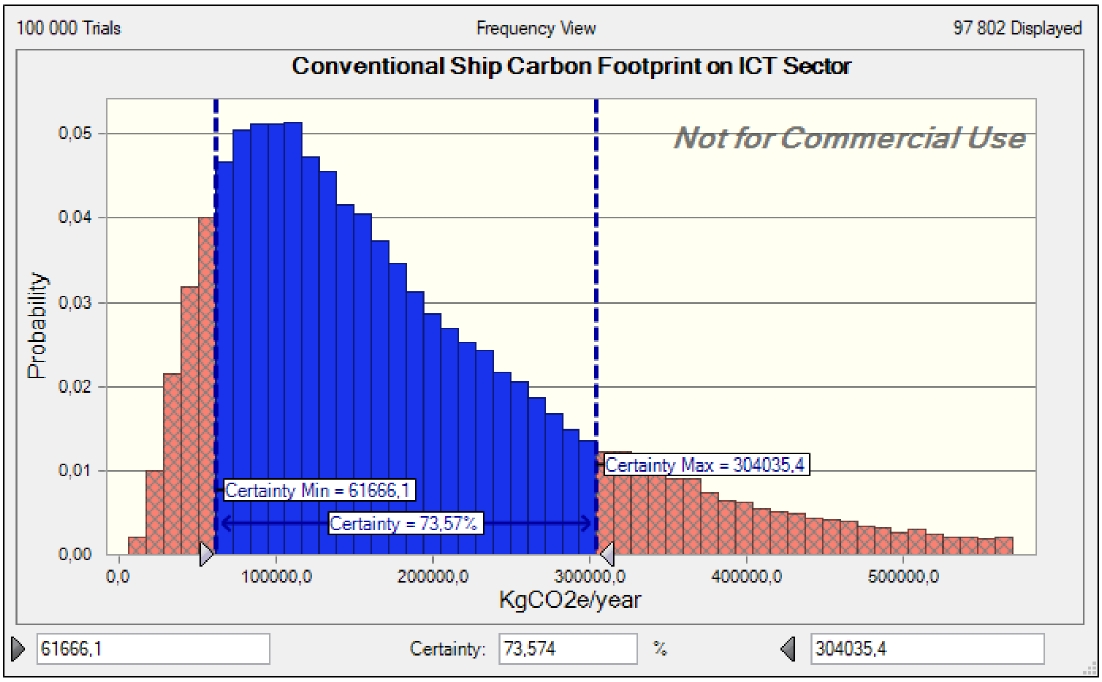

Figure 175. Conventional ship carbon footprint on ICT sector (MSC MATILDE)

In figure 25, the researcher simulates the impact using 100,000 trials to analyses the carbon footprint implications, at 73.574% certainty, MSC MATILDE will contribute between 61,666.1kgCO2e/year to 304,035.4kgCO2e/year. This shows the possible impact that MSC MATILDE contributed to the growing CO2e of the ICT sector.

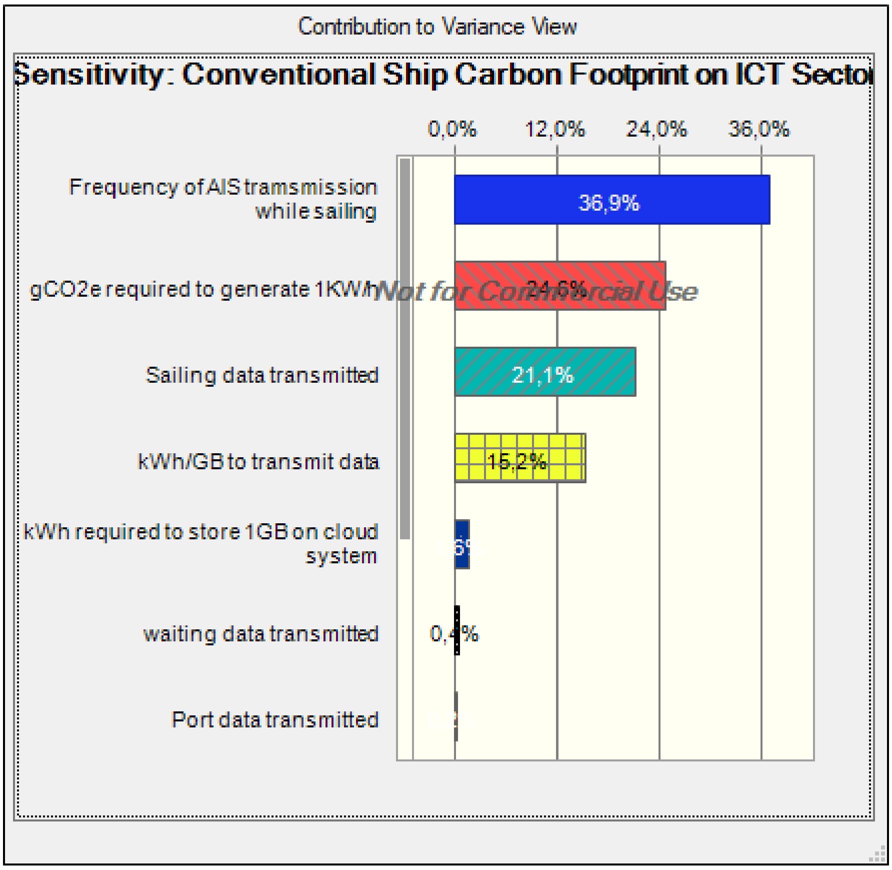

Figure 186. Sensitivity analysis of Conventional ship ICT carbon footprint (MSC MATILDE)

In figure 26, the sensitivity analysis shows the different variables that affect the carbon footprint; the frequency of transmission while sailing positively affects the carbon footprint by 36.9%, the amount of CO2e emitted to generate 1kWh of electricity affects the carbon footprint by 24.6%. Sailing data transmitted affects the carbon footprint by 21.1%, the amount of kWh needed to transmit 1GB of data impacts the carbon footprint by 15.2%, the amount of kWh needed to store/save 1GB of data also affects the carbon footprint by 6% while waiting data and port data transmitted affects the carbon footprints by 0.4 and 0.1 respectively. This shows that the rate at which the AIS is transmitting signals while sailing contribute the large percentage of what affects the carbon footprint as each signal is 50 bytes of data.

Appendix C MASS Carbon Footprint

The researcher calculate the carbon footprint of MASS on the ICT carbon sector with the following assumptions:

- Sailing for 300 days
- Waiting in port for 60 days
- Waiting at anchorage 5 days
- Minimum of 4TB/day data generated by the MASS
- Using emission equivalent of 1bitcoin transaction to provide cybersecurity for MASS
- Using kWh/m2 of non-residential building equivalent to provide electricity to SSC and the equipment building

MASS AIS TRANSMMION RECORDS			
Sailing	=	300	days
Port	=	60	days
waiting	=	5	days
SIZE OF DATA GENERATED			
Sailling		0,1296	**Gigabytes**
Port		0,00144	**Gigabytes**
Waiting		0,00012	**Gigabytes**
Total data Size		0,13116	**Gigabytes**

Table 18. MASS AIS signal transmission.

As shown in table 18, MASS generated **0.13116** Gigabytes of data while transmitting AIS signals to the AIS control Centre.

Using the formula; $d = sailing + waiting + port$

$$d = 0.1296 + 0.00144 + 0.00012 = \mathbf{0.13116\ GB/year}$$

MASS AIS data is ***0.13116 GB/year***;

The researcher calculates the CO2e (*eAIS*) emitted by MASS using AIS.

CO2 EMISSIONS TO TRANSMIT AIS DATA			
Sailling	0,1296	84030068,74	
Port	0,00144	2557,99296	
Waiting	0,00012	213,16608	
Total	84032839,9		Total gCO_2e via AIS data transmission/year

Table 19. 365 days CO2e of MASS transmitting AIS signal

To calculate the CO2e of MASS using AIS, the researcher calculate the CO2e emitted to transmit of Data to AIS control Centre using the formula

Sailing (d) = (0.1296 X eT(300days)) where eT = ***1,776,384gCO2e/ day***

= 0.1296 X (1776384 X 300)

Sailing (d) = ***854030068.74 gCO2e/year***

Port (d) = (0.00144 X eT (60 days))

= 0.00144 X (1776384 X 60)

Port (d) = ***2557.99296 gCO2e/year***

waiting (d) = 0.00012 X eT (5 days)

= 0.00012 X (1776384 X 15)

= ***213.16608 gCO2e/year***

The CO2e emitted by MASS to transmitting AIS signal for 365 days is;

= 854030068.74 + 2557.99296 + 213.16608

$\sum(d\ X\ eT)$ = ***84032839.9 gCO2e/year***

The researcher also calculate the CO2e emitted to store/save MASS's AIS data on the cloud for 365 days using the formula;

eD = d X eD; where eD is 385689600 gCO2e to store/save 1GB of data

= 0.13116 X 385689600

eD = 50587047.9 gCO2e/year

CO2 EMISSIONS STORING AIS DATA ON CLOUD	
50587047,9	Total gCO_2e storing AIS data/year

Table 20. CO2e to store/save MASS's AIS data on cloud system

MASS AIS CO2e (*eAIS*) is;

eAIS = sum of (d X eT) + (eD)

= 84032839.9 gCO2e/year + 50587047.9 gCO2e/year

eAIS = ***134619887.8gCO2e/year***

= 134619.9kgCO2e/year

MASS eAIS	134619887,8	gCO₂e/year
	134619,9	kgCO₂e/year

Table 21. MASS AIS emission (eAIS)

To calculate MASS carbon footprint in the ICT sector, the researcher calculates the CO2e emitted to provide cyber security for the MASS in one year using the emission level of blockchain technology used in bitcoin to securely make transactions.

kW/h REQUIED TO PROVIDE CYBERSECURITY FOR MASS		
1752,79	kWh/day	Assumption based on bitcoin transaction
52583,7	kWh/month	
631004,4	kWh/year	

Table 22. kWh required to provide cybersecurity for MASS per day/month/year

Table 22 shows the kWh requirements to provide cybersecurity for MASS per day/month/year.

CO2e emitted providing cybersecurity for a year is;

eS = 175.79kWh/day X eK

where eK = 14400gCO2e/day

= 175.79 X 14400

eS = 2,531376gCO2e/day

= 2531376 X 30

eS = 75,941280gCO2e/month

= 75941280 X 12

eS = 911,295,360gCO2e/year

CO2 EMISSIONS TO PROVIDE CYBERSECURITY FOR MASS	
25240176	gCO₂e/day
757205280	gCO₂e/month
9086463360	gCO₂e/year

Table 23. CO2e emitted to provide cybersecurity for MASS per day/month/year

To calculate the CO2e emitted from the SCC to monitor the MASS the researcher uses the following formula;

$$eSC = \frac{(xkWh \ X \ ym2 \ X \ eK)}{fleet \ size}$$

x is the value kWh required to produce electricity per square meter, and *y* is the number of square meters of the SCC.

kW/h REQUIED TO POWER SHORE CONTROL CENTRE				
				Source
250	kWh/m2			Assumption based on (European Commission, 2020)
100	m2			Reasonable Asumptions
		25000	kWh/year	
Number of fleet	1			

Table 24. kWh/m2 required to provide SCC electricity per square meter

Note *x* = 250kWh/m2 and *y* = 100m2. The fleet size is 100m2

eK = 14400gCO2eg/day

= 14400 X 30

= 432,000gCO2e/month

=432000 X 12

eK= 5,184,000gCO2e/year

kWh = 250 X 100

= 25000kWh/year

eSC = (25000 X 5184000)/1

eSC = ***1.296E+11gCO2e/year***

CO2 EMISSIONS TO POWER SHORE CONTROL CENTRE	
1,296E+11	gCO2e/year

Table 25. CO2e emitted from SCC to monitor 1 MASS

The researcher calculates the CO2e emitted to store/save data generated by MASS in one (1) year using an assumed value of 4TB per day.

Data generated by MASS is;

4TB X 24days = 96TB/day

96TB X 30days = 2880TB/month

2880TB X 12days = 34,560TB/year

The researcher convert TB to GB

34560 X 1000 = 34,560,000GB/year

DATA GENERATED AND STORED BY MASS				
				Source
4	TB/h			Assumption based on (Ondrej Burkacky et al., 2018)
96	TB/day			
2880	TB/month			
34560	TB/year			
34560000	GB/year			

Table 26. Data generated and stored by 1 MASS per year

The CO2e emitted storing/saving MASS data on cloud is;

34,560,000GB/year X CO2e to store/save 1GB of data on cloud

= 34560000 X 385,689,600

= 1.3329433E+16

CO2 EMISSIONS TO STORE DATA GENERATED BY MASS		
1,33294E+16	$gCO_2e/year$	

Table 27. CO2e emitted during storing/saving data generated and stored by 1 MASS per year

MASS carbon footprint on ICT sector is calculated using the formula the following formula;

$$mcfp = \sum(eAIS + eS + eC + eSC)$$

= ***134619.9kgCO2e/year*** + *911,295,360gCO2e/year* + ***1.296E+11gCO2e/year*** + 1.3329433E+16

= 1.33296E+16gCO2e/year

= 1.33296E+13kgCO2e/year

= **13,329,571,397mtCO2e/year**

MASS CF ON ICT SECTOR	1,33296E+16	$gCO_2e/year$
	1,33296E+13	$kgCO_2e/year$
	13329571397	$mtCO_2e/year$

Table 28. MASS carbon footprint per year

Monte Carlo simulation using Crystal Ball analysis (MASS)

The impact of MASS on the ICT sector carbon footprint with 65.494% degree of certainty is shown in Figure 27 below after running Monte Carlo crystal ball simulation.

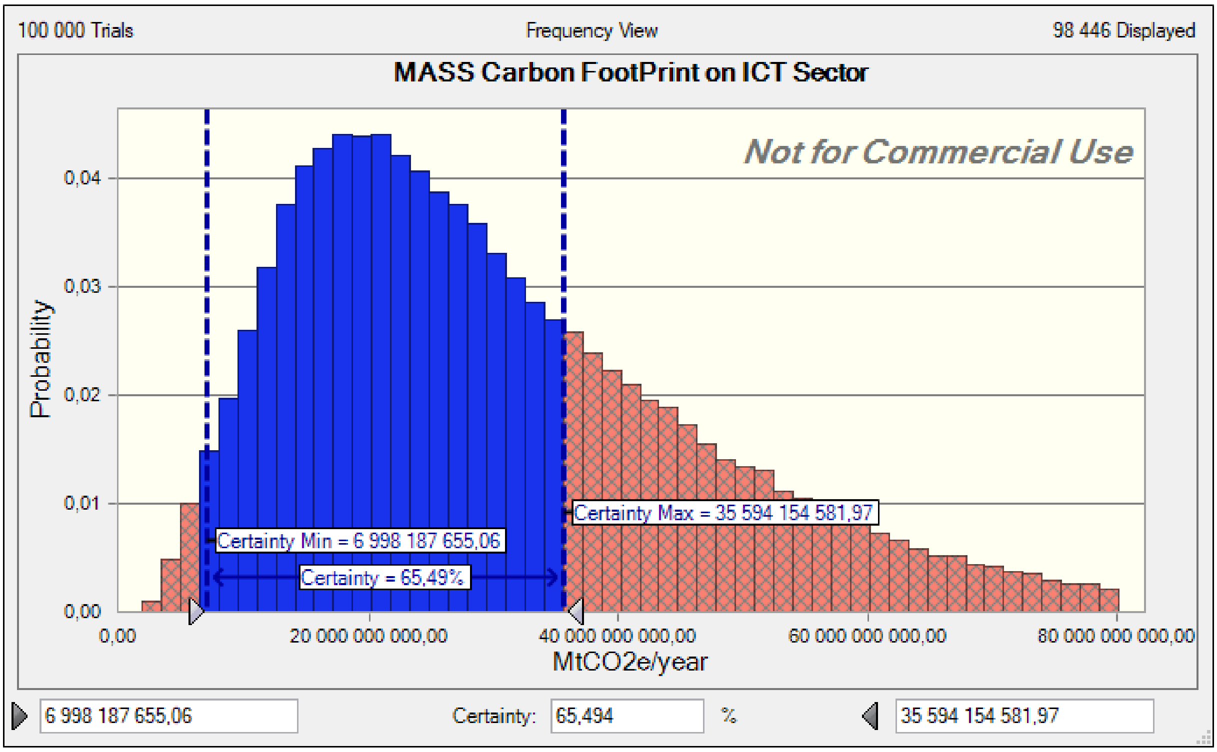

Figure 197. MASS carbon footprint on ICT sector

In figure 27, the researcher simulates the impact using 100,000 trials to analyses the carbon footprint implications, at 65.494% degree of certainty; The analysis shows that MASS will contribute between 6,998,187,655.06mtCO2e/year to 35,594,154,581.97mtCO2e/year. The analysis shows the possible impact of MASS to the growing CO2e of the ICT sector.

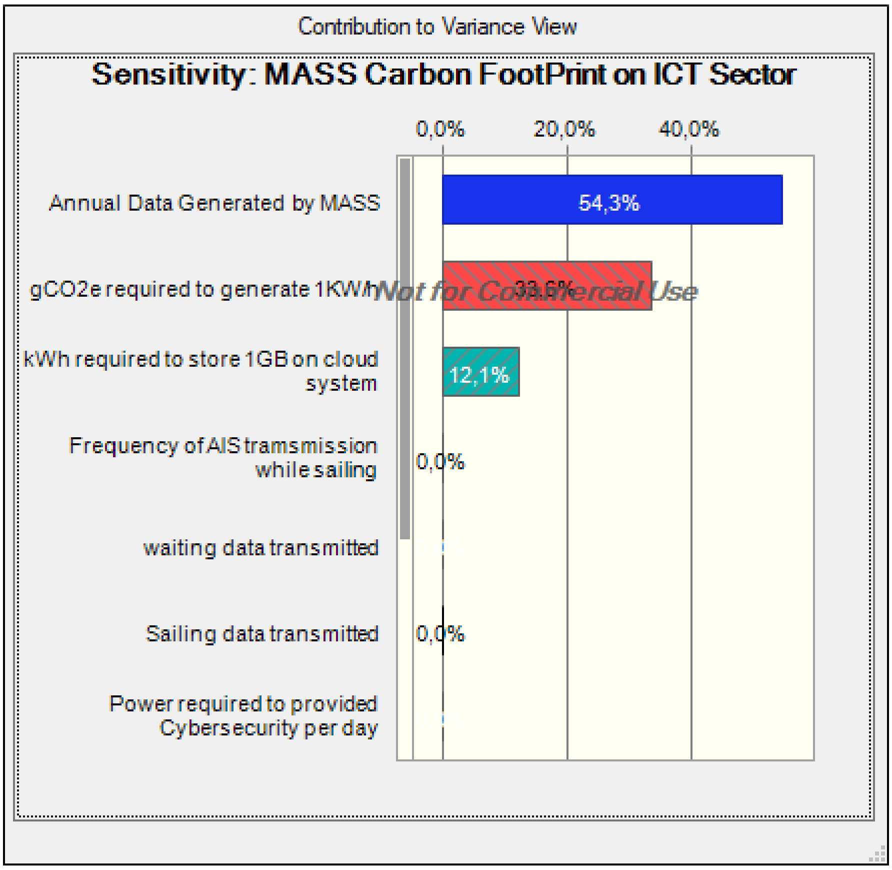

Figure 208. Sensitivity analysis of MASS ICT carbon footprint

Figure 28 shows the sensitivity analysis on the different variables that affect the carbon footprint; the annual data generated by MASS positively affects the carbon footprint by 54.3%, the amount of CO_2e emitted to generate 1kWh of electricity affects the carbon footprint by 33.6%. The amount of kWh needed to store/save 1GB of data also affects the carbon footprint by 12.1%. The emissions from providing cybersecurity affects the carbon footprint with 0.1%.