Hydrogen Usage Estimate of a Crew Transport Vessel Fleet for Offshore Windfarm Maintenance

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***Abstract*—Using hydrogen fuel may help to decarbonize maritime transportation. This paper presents an estimate for the mass of hydrogen that would be needed to power the current fleet of crew transport vessels used for maintaining the German offshore wind farms. The estimate is based on a calculation of the marine diesel oil consumption of the current fleet. We use vessel position data, weather data, and diesel consumption estimates to perform this calculation. Various hull shapes are used in small coastal vessels. This creates a challenge to estimate their energy needs. As a shortcoming, certain effects are excluded from the current estimate. However, this work presents an approach that can be improved and used for estimating hydrogen consumption in future scenarios. In these scenarios, a vessel type and parameters can be set. While here the challenge was to create a generic model that can be applied to multiple types of vessels.**

***Index Terms*—hydrogen, offshore wind farm, maintenance, crew transport vessel**

I. INTRODUCTION

Decarbonization of the maritime industry is an essential aspect of slowing the global warming that is driven by greenhouse gases. The German government has taken action to reduce these emissions. Its hydrogen strategy aims to establish hydrogen as a decarbonization option [1]. The push for green energy production in Germany will increase the reliance on offshore wind farms (OWFs) [2]. Offshore hydrogen production is foreseen in these plans. The hydrogen strategy calls for identification of areas that can be used for offshore hydrogen production [1] and the offshore wind energy law anticipates the construction of hydrogen pipelines [2].

However, a problem with many renewable energy sources is that the production rate is not constant. The rate may depend on wind speed or the amount of solar radiation. The so-called ”Power to X” concept aims to fix this issue [3]. In this concept, the electricity is transformed into another form to store the energy when it is needed. For example in Germany, the AquaVentus initiative pursues this concept for OWF [4]. They seek to produce hydrogen with the energy provided by OWF in the North Sea. Therefore, we assume that hydrogen should be readily available in future OWFs.

Availability of the hydrogen will create an opportunity to use it to power the vessels needed for OWF installation and operational phases. During the operations, Crew Transport Vessels (CTVs) are used for transporting maintenance personnel to perform their activities. As will be described in section II, currently these vessels use Marine Diesel Oil (MDO). If a suitable operation radius can be established with hydrogen-fueled vessels, this can further reduce the carbon footprint of OWFs.

Our contribution presents a calculation of the amount of hydrogen needed to maintain the current German OWFs. This calculation is based on OWF maintenance operations, as observed in stored Automatic Information System (AIS) data. Maritime vessels use the AIS to communicate their locations to other vessels and vessel tracking services. Section III provides details on material for calculation and section IV on the methods. The results are presented in section V.

There are two issues in the presented results. Estimating the effects of the weather on small vessels is complicated due to various hull shapes and the lack of estimates that are only available for large ships [5]. Secondly, the authors had access to a limited data set for validating results. Section VI discusses the validation issue and the paper ends with section VII on conclusions and future work.

II. BACKGROUND ON CREW TRANSPORT VESSELS AND THEIR PROPULSION

CTV is a ship that is used to transport service technicians to OWF [6], [7]. Since a CTV is only designed for transport, the ship is significantly smaller than a service operation vessel. Fig. 1 shows different types of hulls used in coastal vessels[1]. Today, these vessels are most commonly powered by diesel engines. Fig. 2 illustrates this powering system.

Several tests have been conducted to use fuel cells to power small vessels or as an auxiliary power unit for large vessels [9]. Furthermore, the use of fuel cells in coastal vessels has been studied [7], [8]. However, a review of the potential of hydrogen in maritime applications concluded that hydrogen fuel cells will not replace the existing multi-megawatt main engines of large ships in the foreseeable future [10]. But where a low power demand or only a regional fuel supply is necessary, hydrogen-fueled systems can be applied.

Fig. 3 illustrates a hydrogen-powered fuel cell propulsion in a CTV, where hydrogen is fed to a Polymer-Electrolyte

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[1] The source [8] of Fig. 1 is published under the CC-BY-4.0 license.

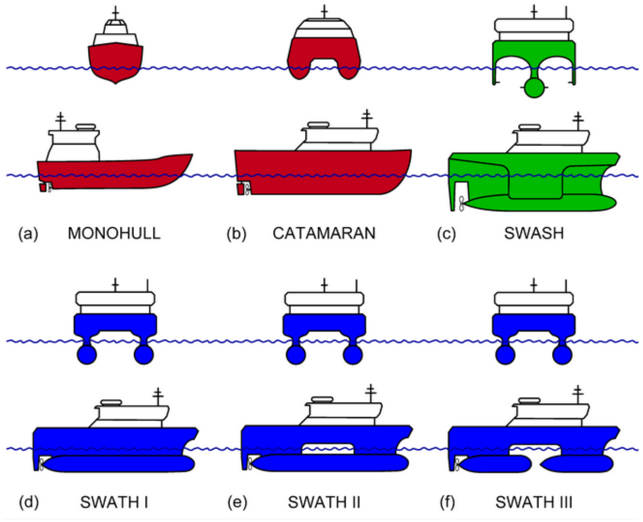

Fig. 1. Comparison of hull shapes for coastal vessels [8].

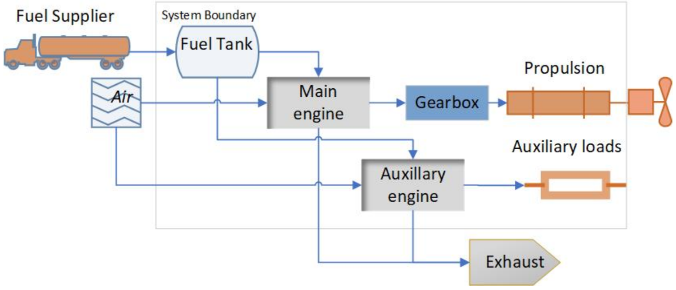

Fig. 2. Illustration of a diesel powering system onboard a CTV.

Membrane (PEM) fuel cell. Produced electricity can power the vessel or it can be stored in a battery. These types of fuel cells have several advantages: 1) high electricity production efficiency, 2) good response time of cell systems, 3) short start-up time, and 4) low operating temperature [9]. Therefore, they have been the most popular option in ship projects.

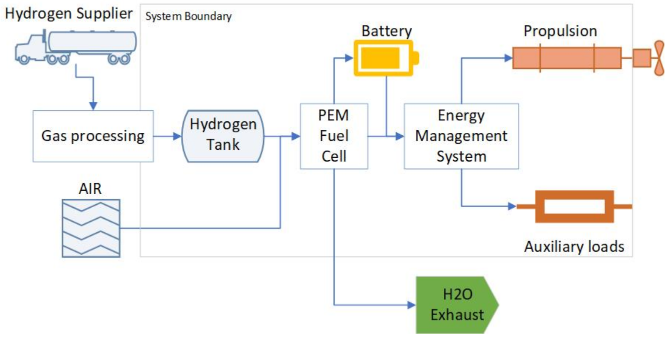

Fig. 3. Illustration of a hydrogen fuel cell powering system onboard a CTV.

The premise of this paper is that CTVs would be bunkered by hydrogen produced in OWF. Fig. 4 shows the hydrogen production process based on [11]. First, hydrogen is produced through the electrolysis of water. Then it is transformed into a liquid form both by compressing it and by cooling it in a liquefier. A more thorough description of this process is also given in [12].

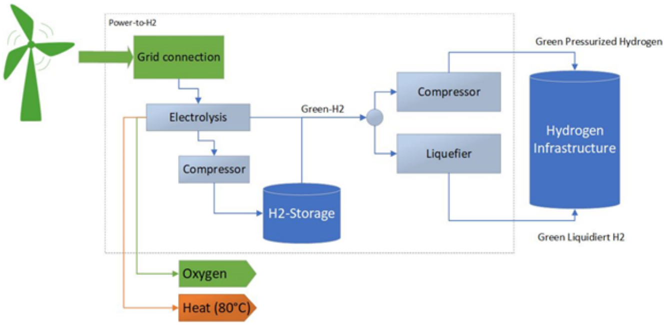

Fig. 4. Hydrogen production process based on [11].

III. MATERIAL

Our work utilizes AIS data, weather data, and vessel characteristics to calculate MDO consumption. We use commercially available AIS data that were collected from terrestrial and satellite sources [13]. We use data from the German exclusive economic zone in the North Sea from the year 2020.

Unfortunately, no convention would allow filtering OWF maintenance vessels from AIS data. The AIS data contains information about the ship type, but this information is not standardized. So entries like ”Ferry” or ”Offshore Supply Vessel”, as well as spelling errors are possible.

Therefore, the following procedure was used for forming a list of vessels. First, all available data of 23218 entries, representing individual vessels, were filtered based on the vessel dimensions. Then, from the remaining 10327 entries, certain vessel categories were removed, e.g. dredgers. Finally, the remaining 353 entries were manually verified, which resulted in a list of 73 entries. The full list of selected vessels is given in Appendix A. This list is an estimate. An exact number of CTVs to maintain German OWFs could not be determined since this information is not publicly available.

A power utilization curve for an example vessel was received from a commercial shipping yard. It shows the percentage of power required to maintain a certain speed, without the effects of weather.

We further studied how the weather affects the resistance. For this purpose, we use the ERA5 weather data-set [14] that consists of hourly estimation of various weather characteristics. These data are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).

Section VI compares the calculated estimates to real MDO usage values. These data were received from a global energy sector company.

IV. METHODOLOGY

The methods for vessel propulsion calculations are well established. Reference [15] gives a practical overview of these methods and is the main source of this section.

For a vessel to maintain a set speed, it has to produce a sufficient thrust to overcome the resistance. The total resistance that opposes the vessel's motion can be calculated with equation

$$R_{tot} = R_{calm} + R_{wind} + R_{wave} + R_x, \tag{1}$$

where R_{calm} is the so-called calm water resistance, R_{wind} wind resistance, and R_{wave} wave resistance. R_x combines different sources of resistance including those caused by steering, marine fouling, tides, and propeller cavitation.

Calm water resistance is the resistance that a CTV would encounter if the effects of the weather are neglected. An example of a resistance curve for a catamaran is given in Fig. 5. The speeds above 16 nm/h are not available and were extrapolated[2]. This is unfortunate, as Fig. 6 shows that CTVs in our data cruise with speeds above this limit.

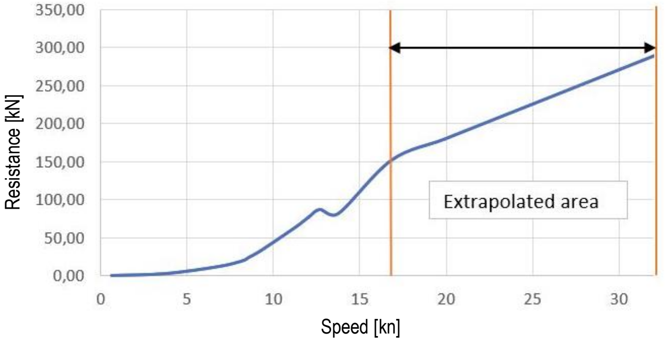

Fig. 5. Calm water resistance for a catamaran [16].

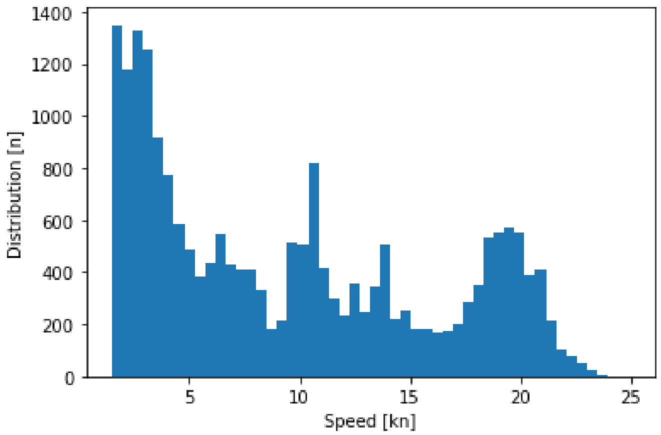

Fig. 6. CTV speed distribution in the data set.

The wind resistance is calculated with equation

$$R_{wind} = \frac{1}{2}\rho_{air} C_w A V_{eff}^2, \tag{2}$$

where ρ_{air} is the air density, A is the area that is subject to wind resistance, and V_{eff} is the effective wind speed that takes into account the vessel's speed [15].

Authors are aware of measured C_w values for large ships [17]. However, we consider that a semi-sphere is a more representative shape for an aerodynamic CTV than a container or a cruise ship. Therefore, we use values from [18], which are shown in Table I. Area A also depends on V_{eff}. We estimated the values based on the dimensions of our reference vessel, which are also shown in Table I.

TABLE I
NUMERICAL ESTIMATES FOR EQ. 2

Wind direction [°]	C_w	A **[m²]**
0-45	0.33	76
45-90	0.15	111
90-135	-0.15	111
135-180	-0.33	76

Resistance due to high seas i.e. weather waves depends heavily on the ship length and wave length [15]. In addition, the waves also set the ship in motion. This leads to added resistance as more water is affected by the movement of the ship. Also, more rudder corrections will be needed to stay on course. Due to these reasons, R_{wave} is currently excluded from the analysis. We further assume that R_x is small compared to other summands in equation 1.

The resistance would be transformed into the power demand by calculating the required towing power

$$P_{T\_i} = R_{tot} V, \tag{3}$$

and estimating the required engine power by taking into account different efficiencies

$$P_i = \frac{P_{T\_i}}{\eta_H * \eta_S * \eta_R * \eta_{RP}}. \tag{4}$$

The ranges for the efficiency values are: hull efficiency $\eta_H = 0.95 - 1.05$, shaft line efficiency $\eta_s = 0.9 - 0.99$, rotational efficiency $\eta_R = 1 - 1.07$, and free running propeller efficiency $\eta_{RP} = 0.35 - 0.75$ [7].

As described, there were issues with the available resistance curve, coefficient for equation 2, and estimating R_{wave}. Therefore, we use a power utilization curve from a commercial shipping yard. In this curve, resistances are already transformed into the power utilization percentage of the engine. In Fig. 7, the red curve shows information from a shipping yard, to which an "artificial" curve is fitted. The newly created plot is based on polynomial interpolation of the yard data. The green curve shows an example of how the weather correction increases the required power to maintain a certain speed.

The utilization curve is for a specific vessel. However, based on its dimensions, the curve provides a good basis for estimating the other CTVs. Fig. 8 shows the dimensions of this specific vessel compared to the list of vessels we selected for our analysis. The most important ones relate to the vessel's draught, and length. Length L, width B, draught T, and volume of displacement Δ are used for calculating a so-called block coefficient [15]

$$C_B = \frac{\Delta}{LBT}. \tag{5}$$

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[2] 1 nm = 1852 m; 1 nm/h = 1 kn

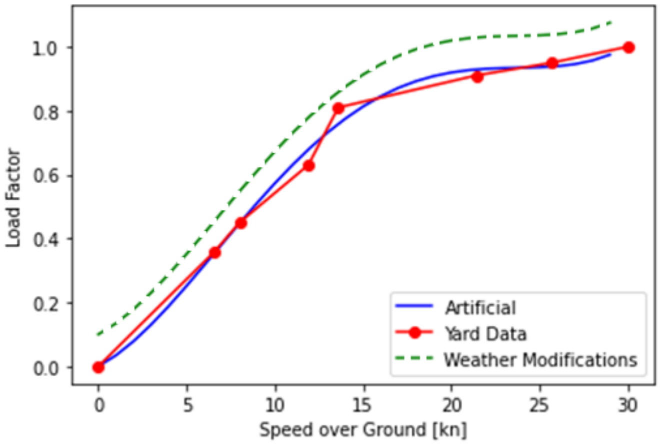

Fig. 7. Example of power utilization percentage for different vessel speeds.

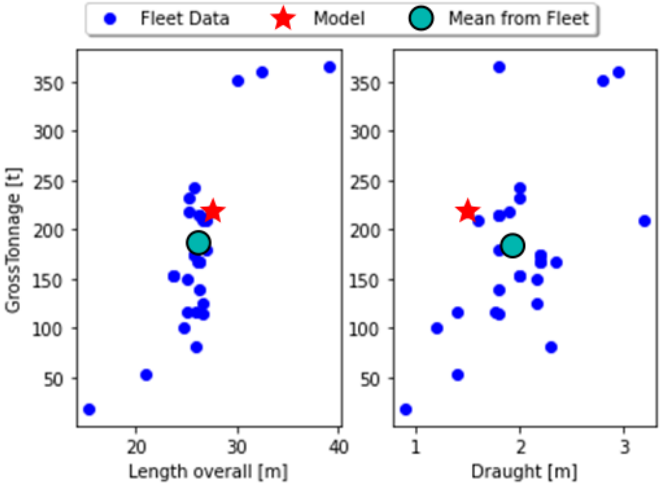

Fig. 8. Resistance model vessel parameters compared to fleet data.

Reference [15] states that it is the most important coefficient to express the shape of the hull. However, as most CTVs have a multi-hull structure, the width of the vessel is a less important factor than in mono hull vessels. The tonnage of a vessel defines its Δ. As, based on Archimedes' principle, the weight of an object is equal to the weight of the fluid (water) it displaces.

Power utilization depends also on vessel operations. CTVs consume large amounts of MDO during a so-called ropeless mooring to a wind turbine. In this operation, a CTV pushes against a turbine with 70% power utilization. To take these operations into account, we assume that a CTV is pushing when it is stationary ($V < 1$ nm/h) for not more than 30 min. If a CTV is stationary for more than 30 min, we consider it to be in idle mode.

The MDO and hydrogen consumptions are estimated similarly as in [12]. The mass of the consumed MDO is calculated with equation

$$m_{MDO} = \sum_{i=0}^{n} (P_{ME\_i} * SFOC_{ME\_i} + P_{AE\_i} * SFOC_{AE\_i}) \Delta t_i, \tag{6}$$

where P_{ME_i} and P_{AE_i} are power for the main engine and auxiliary engine during the time step Δt_i. $SFOC_{ME\_i}$ and $SFOC_{AE\_i}$ are instantaneous MDO consumption for these engines during the time step. The mass is calculated by summing the consumption over all time steps 0 - n. We make the following assumptions

1) $SFOC_{ME\_i} = 185$ g/kW/h for a modern high-speed vessel [19];
2) auxiliary power usage results in 150 l MDO consumption per day independent from a CTV use.

The hydrogen consumption is estimated with equation

$$m_{H2} = \frac{P_i \Delta t_i}{\eta_{FC} LHV_{H2}} \tag{7}$$

where P_i is the power demand during a time step Δt_i , $\eta_{FC} = 50\%$ is the fuel cell efficiency, and $LHV_{H2} \approx 33.3 \frac{\text{kWh}}{\text{kg}}$ is the lower heating value [20].

V. RESULTS

When the methods described in section IV are applied to data presented in section III following results are obtained:

- total sailed distance of all vessels $2 * 10^6$ nm (27647 nm per CTV);
- total MDO consumption 40745 t (558 t per CTV);
- total hydrogen consumption 13849 t (187 t per CTV);
- average CTV utilization time 204 days.

Fig. 9 shows the consumption values for individual months as well as the distance traveled by individual vessels.

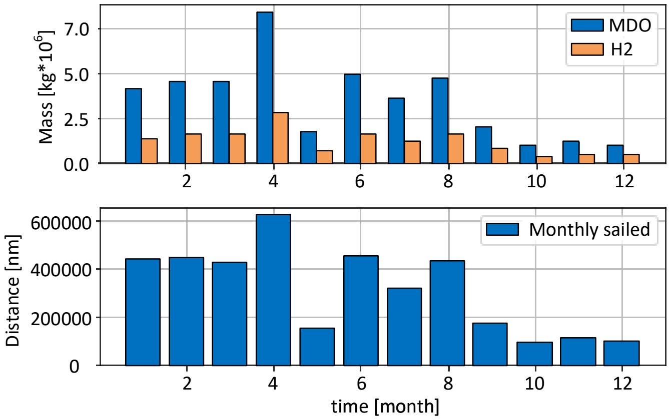

Fig. 9. On the top, estimates for MDO and hydrogen consumptions, and on the bottom, vessel activity for individual months in 2020.

To estimate the effects of the weather, we compared the air resistance and wind resistance. Air resistance R_{air} only accounts for the calm weather resistance from moving the ship through the atmosphere without any wind [15]. Wind resistance R_{wind} is calculated in the same way as R_{air} but takes into account the combined speed of the ship and the wind. Both were calculated with eq. 2 and the ratio

$$\frac{R_{air}}{R_{wind}} = 0.77. \qquad (8)$$

This result means that at least when only the wind speed is considered, the effect of the weather is limited.

VI. DISCUSSION

Ideally, the resulting MDO consumption should be compared with the real values to verify the used approach. The authors have nine measurements of annual CTV MDO consumption received from a global energy sector company. However, these data cannot provide statistical proof to verify the method or assess the error. The reasons are that the sample is too small, and it is not randomly chosen, as it consists of vessels operated by a single company. Therefore, the data are only shown as evidence of method viability.

Fig. 10 shows the average MDO consumption calculated from the results in section V compared to actual consumption values from nine measurements from the years 2020 and 2021. The average calculated consumption is lower than the actual one. This is expected as the resistances caused by weather and maneuvers are excluded from the calculations. However, the difference is lower than what could be assumed based on references [7], [8].

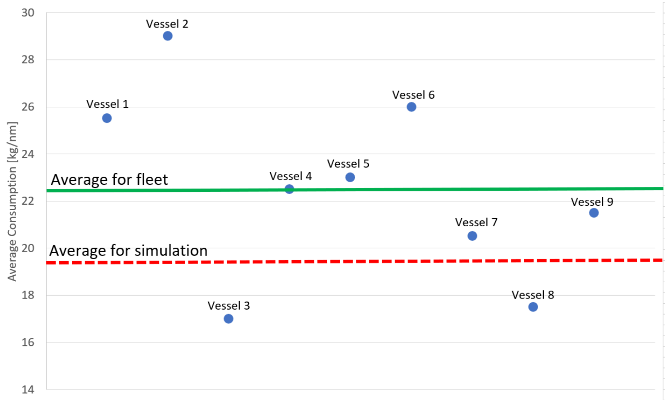

Fig. 10. Real MDO consumption data compared to the mean result of the calculation.

Interestingly, the results in Fig. 9 further show a dent in activity in the May of 2020. Coronavirus became a global pandemia during the spring of 2020 and caused nations to enact restrictions on movement to slow the spread of infections [21]. The authors suspect that the dent is a result of these restrictions.

VII. CONCLUSIONS AND FUTURE WORK

This paper presented a calculation of the amount of hydrogen needed to maintain the current German OWFs. The estimate was based on a calculation of the MDO consumption of the current fleet. The calculation in turn was based on OWF maintenance operations, as observed in stored Automatic Information System (AIS) data.

This calculation was challenging as various hull shapes used in small coastal vessels complicate the estimation of their energy needs. As noted in section IV, the current shortcoming is that certain weather effects are excluded from the estimate. Therefore, at the moment the estimated consumption is too small. A comparison with a sample of real data was performed in section VI. The average consumption for the sample vessels is higher than our estimate. However, the sample is too small and it is not randomly selected. Therefore, statistical methods to measure the error cannot be used.

In this paper, the issue was to form a generic approach that can be applied to all CTVs that are now used in Germany. Future studies may improve the approach. However, it might be more interesting to apply this approach to future scenarios where resistance can be estimated for a selected vessel type rather than all used vessels. This kind of scenario could, for example, estimate the needed hydrogen to maintain a selected set of OWFs.

Authors believe that hydrogen should be readily available for OWF maintenance vessels in the future. This is thanks to the German hydrogen strategy that emphasizes the Power to X concept [1]. Shifting away from MDO to CTVs using hydrogen creates an opportunity to further decrease the carbon footprint of OWFs. Thus, resulting in more environmentally friendly energy production.

ACKNOWLEDGMENT

This paper uses data from Copernicus Climate Change Service information (accessed 2021). Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

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APPENDIX A
LIST OF VESSELS IN THE ANALYSIS

This appendix provides the Maritime Mobile Service Identity (MMSI) numbers [22] for the vessels included in the MDO consumption assessment of the current CTV fleet to maintain the German OWFs. The numbers are in a comma-separated list: 211471230, 211647900, 211666720, 211755490, 211766470, 211810060, 219014434, 219014436, 219015382, 219016747, 219016873, 219017205, 219018007, 219019933, 219019936, 219020687, 219023785, 219023786, 219024900, 219026749, 219027299, 219142000, 219447000, 219459000, 219463000, 219464000, 219472000, 219513000, 219770000, 219811000, 220626000, 232005600, 232005627, 232006483, 232013230, 232013231, 232013884, 232013885, 232020271, 232020872, 232025959, 232026644, 232027488, 232027489, 232028492, 232031335, 232031394, 235068679, 235080246, 235084702, 235091254, 235095777, 235095778, 235096275, 235098051, 235102028, 235102689, 235103265, 235103385, 235103429, 235108494, 235108711, 235111197, 235111522, 235116577, 235116578, 235117937, 236112545, 244650652, 244830667, 244830668, 253664000, 374011000