Floating Power Platforms for Offshore Cold-ironing

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Abstract The colloquial term ‘cold-ironing’ refers to connecting a ship to shore power when it is at berth, as its main and auxiliary engines, made of steel/iron, are shut down, literally becoming cold. In the current environment where strict emission regulations govern virtually every ship operation, shore power has become an essential service sought by ships at berth in emission controlled ports. At present, these ships in port can receive shore power only when they are at berth, usually during the transfer of cargo or passengers. However, there are many more ships anchored in and around the ports awaiting access to berths. Efficient supply of shore power to these anchored ships is a challenge and thus they rely on their on-board power generation systems to supply essential loads. As the waiting time can vary from a few hours to weeks, emissions from these ships are significant, especially as they are clustered together in close proximity to land. Therefore, if an efficient and effective way of powering anchored ships with clean or low emission power is available, it can significantly contribute towards reducing emission around busy ports as well as the operating cost of anchored ships.

In an attempt to address this problem, authors propose a floating power platform for ‘offshore cold-ironing’. The proposed system consists of a fuel cell, a battery bank, and a small LNG engine driven generator set installed on a floating platform such as a barge and moored in close proximity to the anchored ships to supply them with their required electrical power. Nowadays, with the advancements of the fuel cell technology, installation of a suitable fuel cell stack on a floating platform such as a barge has become feasible. Nevertheless, fuel cells response slowly and thus fast dynamic loads such as dynamic positioning load in adverse sea conditions can easily push the fuel cell beyond its safe operating range, possibly creating power system instabilities that can result in blackouts. In addition, the floating platform itself needs dynamic positioning or some form of control to maintain its position relative to supplied ships, further influencing the dynamic load.

The battery bank can support the fuel cell to cope with such loads. However, in extreme situations, even the battery bank will discharge rapidly and the fuel cell may struggle to charge it. Therefore, when the state of charge of the battery bank drops below a defined lower threshold, the LNG engine-driven generator set starts and provides boost power to charge the batteries. As the generator is used only when the battery charge is low, and the emission from the LNG is relatively low in comparison to other fossil fuels used on-board, the proposed system can be considered as a low emission technology solution. The feasibility of the proposed concept of floating power platform, from the power system control perspective, is investigated in this paper through modelling and simulation, with the results clearly showing the efficacy of the proposed hybrid power system to supply the dynamic loads encountered on anchored ships.

Keywords: Battery, cold ironing, fuel cell, LNG engine, power management, shore power.

1. Introduction

Shipping is considered essential for the growth of the global economy as it accounts for more than 90% of the goods transported locally and internationally [1]. Therefore, current economic and population growth across the world requires a complementary growth in the shipping industry, with greater demand for the number and size of ships plying the major economic routes. Unfortunately, this results in a greater use of fossil fuels, in turn increasing the global share of greenhouse gas (GHG) emissions from ships and thus contributing significantly to climate change and other environmental issues [2, 3]. In an attempt to reduce these emissions, many countries and regions have imposed strict emission regulations and defined emission control areas (ECAs) around their coasts [4, 5]. Ships that visit ports in these areas or sail through these regions are required to take measures to comply with emission regulations [6]. Cold-ironing is one such measure where ships at berth shut down their relatively high emission engines and receive power from shore connections [7, 8]. Even though the generation of shore power may use similar fossil fuel, (e.g. diesel fuel), it is possible to do so within a more controlled environment and thus can yield to a net reduction in emissions [9]. Thus, the use of shore power is increasing in popularity in comparison to running on-board engines.

At present, ships can receive shore power only when they are at berth for cargo operations or passenger transfer. Ships at anchor, waiting for their turn, are unable to access shore power. Currently, there is no efficient and effective way to supply them with shore power and thus on-board main and/or auxiliary engines have to supply essential loads. As the waiting time can vary from a few hours to weeks, emissions from these ships could be significant. Therefore, an innovative solution is required for the efficient and effective supply of clean or low emission power for anchored ships, especially around busy ports such as in Singapore.

As proposed in [10] an offshore floating renewable power station is a promising solution for supplying anchored ships with clean power. The ‘offshore cold-ironing’ platforms presented in this paper is a continuation of this idea. An overview of the proposed system consisting of a fuel cell stack, a battery bank, and a small LNG engine-driven generator is shown in Figure 1. A schematic diagram of the corresponding power conversion system is given in Figure 2. The coupled LNG engine and generator set does not run continuously. It is used only to give a power boost when the battery is discharged below a certain level, and will shut down once fully charged. This ensures low emission due to the sparing use of the engine and the relatively low emissions of the LNG in comparison to other commonly used marine fuels. Therefore, the proposed system can be categorised as a low emission technology solution. The combined system can be installed in a platform such as a barge and moored closer to the anchored ships to supply the required electrical power. As reported in [11], installing a fuel cell power system in a floating platform, e.g. barge, is feasible.

A typical ship power system provides service and propulsion loads [12]. Although service loads may experience fluctuations, their magnitudes and rate of change usually fall within operational envelop of fuel cells. However, difficulties arise with propulsion loads that are linked to dynamic positioning, especially at rough sea conditions. Similarly, the moored platform may not hold to its position during a rough sea and therefore a suitable control mechanism is required for position fixing. Therefore, load dynamics caused by propulsion motors and thrusters can easily push the fuel cell away from the stable operating region causing blackouts. In such situations, the battery bank can support the fuel cell to keep it within its operating envelop. When the combined fuel cell and battery system is unable to supply the load, the LNG engine is started automatically to supply a power boost. These combined operations bring complexities into the proposed floating power system and thus its performance heavily depends on the effectiveness of the control and power management technologies used within the system.

Various control and power management schemes are proposed in relevant literature for similar hybrid power systems. These techniques can be broadly classified as traditional PID based controls [13-16], model reference based controls [17-19], and learning based controls [20, 21]. Out of these three categories, the traditional PID based controls are the simplest and thus the most widely used. Nevertheless, model reference based control schemes render fast transient response while learning based controls are generally immune to parameter changes. As the focus of this paper is to investigate the feasibility of the proposed system, simple PI controllers and a straightforward power management strategy which is based on the battery state of charge measurement were adopted. In this study, the proposed system, its control scheme and the power management were modelled in the MATLAB/Simulink environment, with simulations carried out to test their performance under dynamic loading conditions. Simulation results show that the proposed floating hybrid power system is capable of supplying dynamic loads without triggering blackouts.

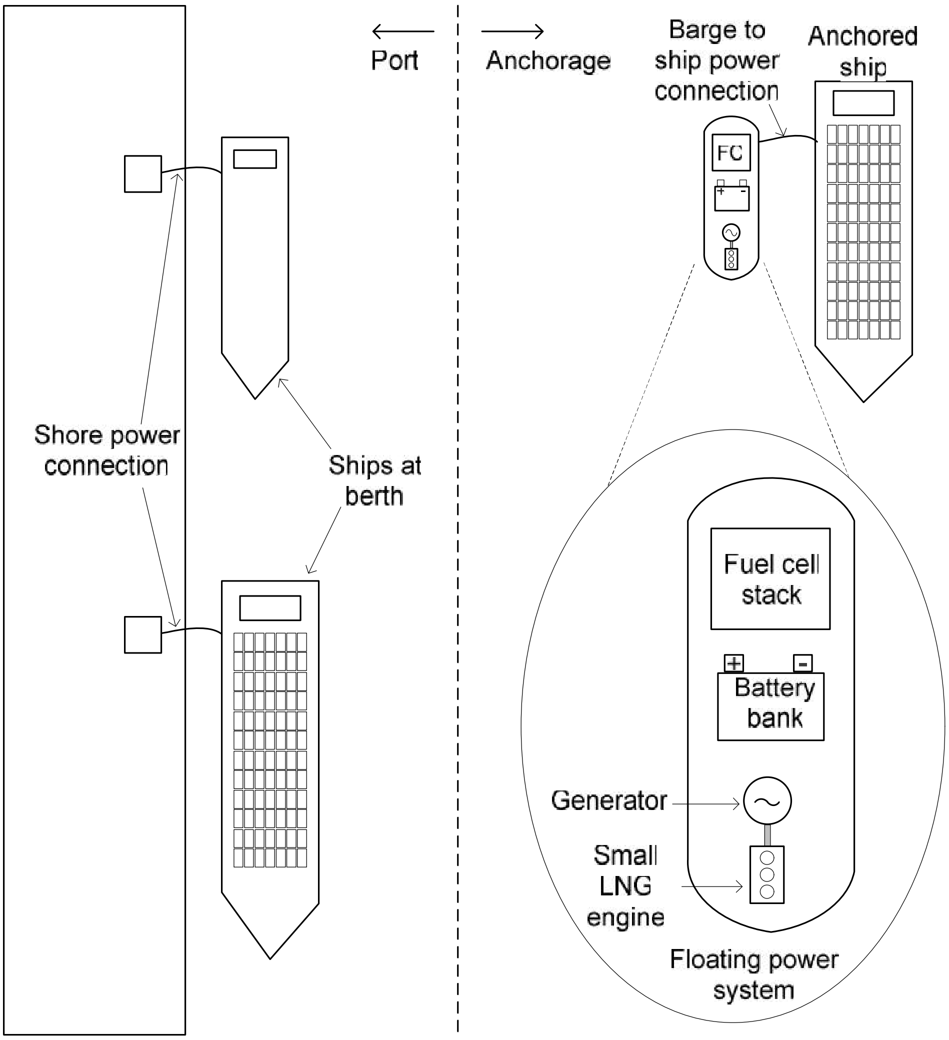


Figure 1 An overview of the proposed system

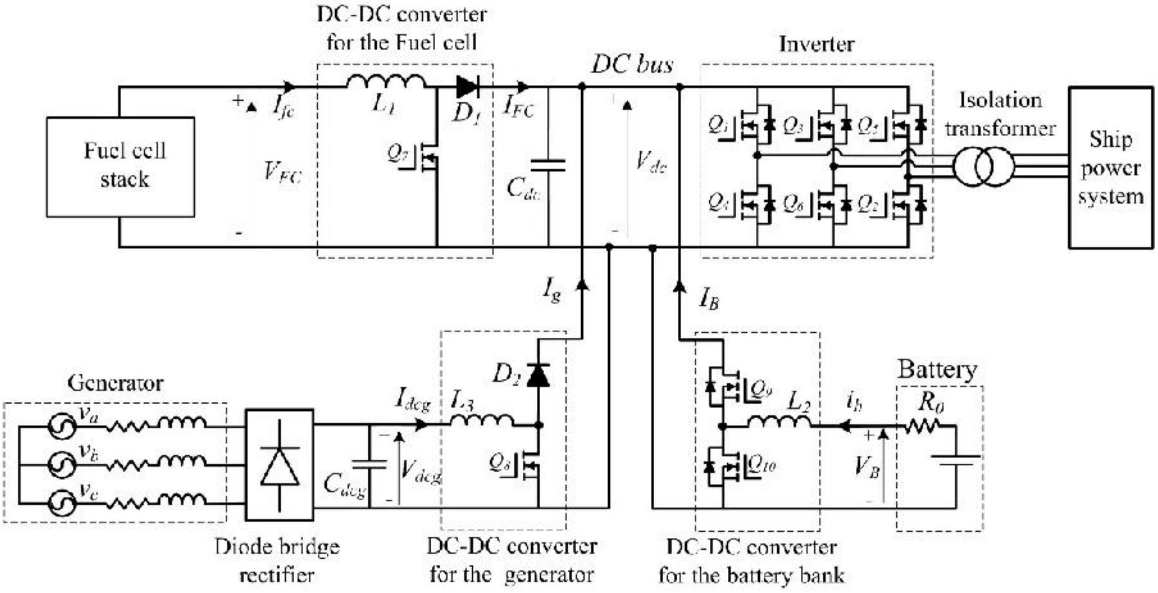


Figure 2 Schematic diagram of the proposed 'offshore cold-ironing' system

2. System Modeling

2.1 Fuel Cell Model

A schematic diagram of the fuel cell model used in this study is shown in Figure 3. In this model, the open circuit voltage (E_{oc}), exchange current (i_0) and the Tafel slope (A) are calculated using equations (1), (2) and (3) respectively [22, 23].

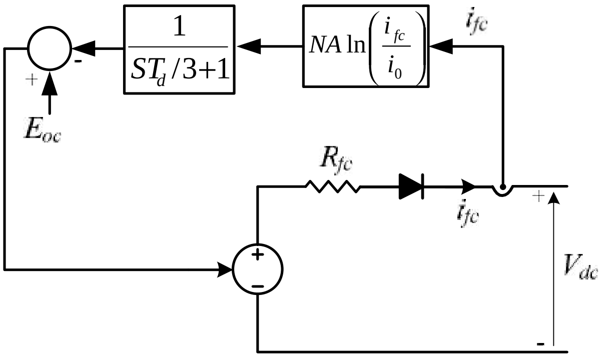


Figure 3 Fuel cell model

$$E_{oc} = K_c E_n \tag{1}$$

$$i_o = \frac{zFk\left(P_{H_2} + P_{O_2}\right)}{Rh} e^{\frac{-\Delta G}{RT}} \tag{2}$$

$$A = \frac{RT}{z{\sim}F} \tag{3}$$

where N is the number of cells in the fuel cell stack, R is the universal gas constant (8.3145 J/mol K), F is Faraday's constant (96485 C/mol), z is the number of moving electrons, E_n is the nernst voltage which is the thermodynamics voltage of the cells that depends on the temperatures and partial pressures of reactants and products inside the stack (V), α is the charge transfer coefficient which depends on the type of electrodes and catalysts used, P_{H2} is the partial pressure of hydrogen inside the stack (atm), P_{O2} is the partial pressure of oxygen inside the stack (atm), k is the Boltzmann's constant (1.38×10^{-23} J/K), h is the Planck's constant (6.626×10^{-34} Js), ΔG is the size of the activation barrier which depends on the type of electrode and catalyst used, T is the temperature of operation (K), K_c is the voltage constant at nominal condition of operation, R_{fc} is the internal resistance of the fuel cell stack, S is the Laplace variable and T_d is the response time (s).

2.2 Engine and Generator Models

The engine is represented as a first order delay with the time constant $^{2}{}_{en}$ as shown in Figure 4. The governor of the engine controls the fuel supply to the engine and thus controls the engine torque, T_{ENG}, to regulate the engine speed under varying load conditions. The corresponding closed loop speed controller of the small LNG engine and the generator set is represented as in Figure 4, where T_e is the electrical load and J_{gen} is the equivalent inertia of the rotating parts.

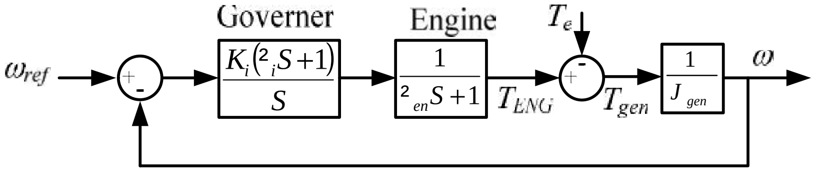


Figure 4 Engine model and closed loop speed controller of the small LNG engine and generator set

3. Control and Power Management

3.1 Fuel Cell Power Controller

The interfacing dc-dc converter, shown in Figure 2, is used to control the fuel cell power by controlling the current passes through it. The corresponding controller block diagram is shown in Figures 5, where P_{fc}^* represents the power reference for the fuel cell stack and V_{FC} represents the fuel cell voltage. The power reference can be adjusted to suite system requirements. Nevertheless, due to the slow dynamics of the fuel cell it cannot respond to fast changes. Therefore, generally, the fuel cell power reference is changed slowly. Hence, in this study, it is set to a constant value which in turn ensures smooth operation of the fuel cell stack. This value is then divided by the fuel cell voltage to generate the current reference, I_{FC}^*. As shown in Figure 5, the actual current passing through the dc-dc converter, I_{FC}, is then compared with the reference and the error is passed through a PI controller to generate the duty cycle, D_{fc}. The duty cycle, which varies between 0 and 1, compared with a triangular carrier signal in the pulse width modulation (PWM) unit to generate gate pulse for the transistor $Q7$.

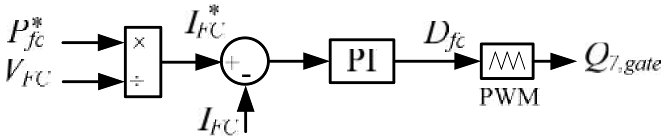


Figure 5 Fuel cell power controller (P_{fc}^*- power reference, V_{FC} - fuel cell voltage, I_{FC}^* - current reference for the interfacing dc-dc converter of the fuel cell stack, I_{FC} - output current of the dc-dc converter, D_{fc}- duty cycle of the dc-dc converter)

3.2 Battery Power Controller

Due to the slow dynamics of the fuel cell, sudden load changes cause deviations in the dc-link voltage. The battery power controller, shown in Figure 6, senses these deviations by comparing the actual dc-link voltage, V_{dc}, against the set value, V_{dc}^*. The error is passed to a PI controller to generate the duty cycle, D_{Bat}, for the corresponding dc-dc converter. As described above, the PWM unit generate gate pulses for Transistors Q_9 and Q_{10} based on the duty cycle. This controller attempts to restore the dc-link voltage. As a result of this voltage restoration effort, battery power varies. This controller is simple and easy to implement as it automatically takes care of both charging and discharging of the battery bank.

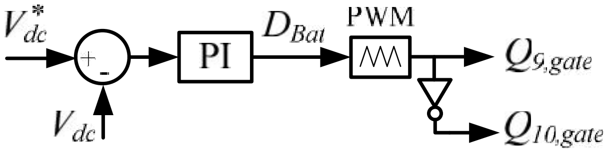


Figure 6 Battery power controller (V_{dc}^*- dc-link voltage reference, V_{dc} - measured dc-link voltage, D_{fc}- duty cycle of the interfacing dc-dc converter of the battery bank)

3.3 Generator Power Controller and Power Management Strategy

A battery state of charge based simple power management strategy is used in this study where the LNG engine automatically starts when the state of charge of the battery bank falls below a certain threshold to provides boost power. For the sake of simulation, the generator power reference P_{gen}^*, was set to a constant value in this study. Whenever the sum of the generator power and fuel cell power exceeds the load demand, the surplus gets stored in the battery bank and thus it gets charged. As shown by the hysteresis block in Figure 7 the generator runs until the state of charge of the battery reaches the upper threshold before cutting out. The corresponding controller is shown in Figure 7.

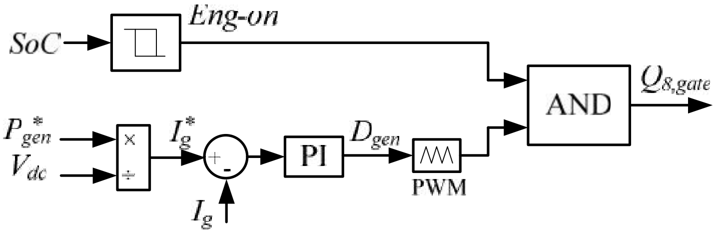


Figure 7 Engine power controller (*SoC* - state of charge of the battery bank, P_{gen}^*- power reference, V_{dc} - measured dc-link voltage, I_g^* - current reference for the interfacing dc-dc converter of the generator, I_g - output current of the interfacing dc-dc converter, D_{gen}- duty cycle of the dc-dc converter)

4. Simulation Results

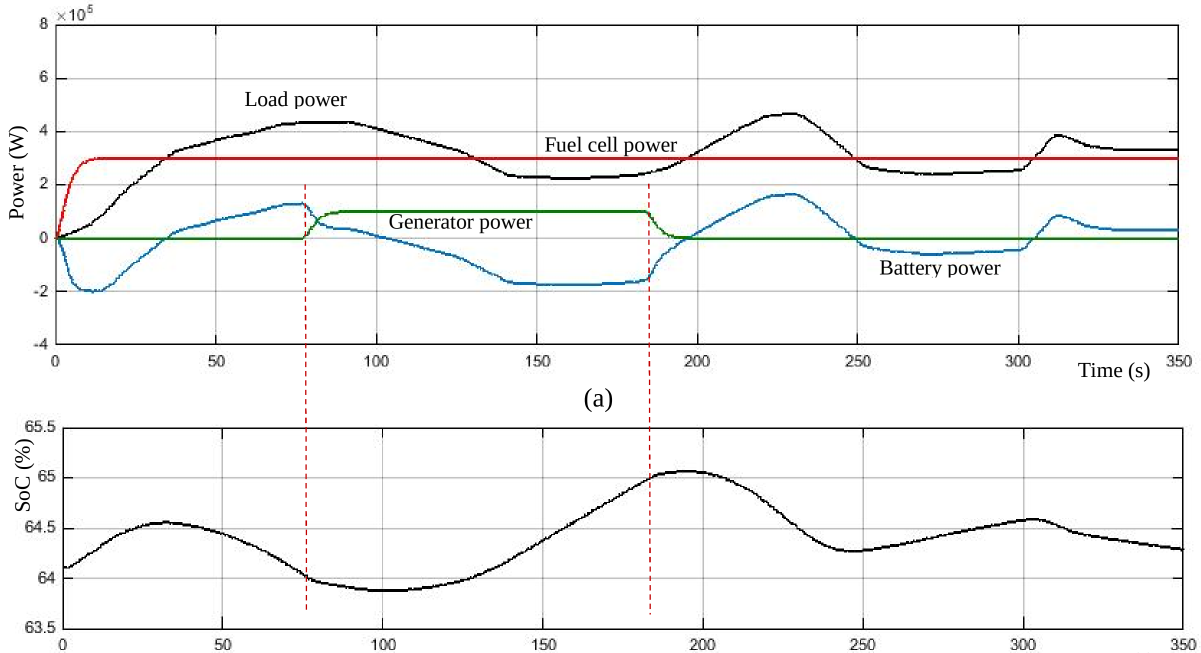
The proposed hybrid power system was modelled and simulated using the MATLAB/Simulink software to test its performance at dynamic loading conditions. System parameters of the simulation setup are given in Table I. Load power variations used in this study are shown in Figure 8(a) by the trace marked 'Load power'[24]. As mentioned above, fuel cell power reference was set to a constant value. As evident in Figure 8(a) by the traced marked 'Fuel cell power' the controller is able to maintain the fuel cell power at the set value. The battery bank absorbs the fluctuations present in the load power as shown in Figure 8(b) by the trace marked 'Battery power'. The negative battery power shown during the 0-30s period indicates that the fuel cell power is larger than the load demand and thus the battery gets charged. The plot of corresponding state of charge variation in Figure 8(b) shows an increase during this period. After that, the load power exceeds the fuel cell power and thus the battery bank is discharged causing its state of charge to drop.

In order to show the performance of the engine power controller, the lower and upper thresholds of the battery state of charge was set to 64% and 65% respectively. Practical values of theses thresholds can be significantly different to these values, depending on the application environment. The points at which the battery state of charge meets these thresholds are marked by vertical dashed lines in Figure 8. When the Battery state of charge drops below 64%, the generator starts and delivers power to the common dc-bus. As mentioned above, the engine power is set to a constant value in this study and thus the corresponding generator power remains constant as shown in Figure 8(a) by the trace marked 'Generator power'.

Whenever the sum of the generator and fuel cell power exceeds the load power, the battery bank is charged. This is evident in the variations of the battery state of charge shown in Figure 8(b). When the battery state of charge reaches 65%, the engine cuts out, thus the generator power drops to zero as shown in Figure 8(a). These results verify the ability of the proposed hybrid power system to supply dynamic loads while ensuring smooth operation of the fuel cell stack through appropriate control and power management.

Table 1 System parameters of the simulation setup

Rated power of the fuel cell stack	350kW
No load voltage of the fuel cell stack	900V
DC-Link voltage reference	600V
Nominal voltage of the battery bank	480V
Maximum capacity of the battery bank	400Ah
Rated power of the generator	100kW
Output line voltage ($V_{LL\text{-}rms}$)	440V
Output frequency	60Hz



(a)

(b)

Figure 8 (a) Load power, fuel cell power, battery power and generator power, (b) State of charge (SoC) of the battery bank.

5. Conclusion

This paper proposes a hybrid power system for offshore cold-ironing of anchored ships, which consist of a fuel cell stack, battery bank and a small LNG engine-driven generator set. In this study, a simple PI controller based control system and a battery state of charge based power management strategy were used to verify the operation of the proposed hybrid power system under dynamic loading conditions. Simulation results show that the fuel cell and battery combination is able to supply dynamic power demands, while the small LNG engine-driven generator provides boost power to charge the battery bank when its charge falls below a set threshold. Based on the results, it can be concluded that the proposed hybrid power system is capable of supplying dynamic loads that can occur in a ship's power system while at anchor, ensuring smooth operation of the fuel cell stack. It is thus a viable option to provide efficient, effective and low emission power to a large fleet of vessels anchored in and around congested ports across the world. Assessing the performance of the proposed system against actual power demands recorded from anchored ships would be a possible step to take the proposed concept to the next level.

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