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CIMAC Guideline

Maritime Hybrid Systems

CIMAC Working Group 20 'System Integration'

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Content

1 Introduction

The Vikings used sails as the main source of propulsion but in addition to that, they had developed wooden oars. The combination of using the main sails and the wooden oars gave the Vikings high reliability in their operation and the maneuverability of their ships compared to other ships in this era. Over time many different technologies in the maritime field have been developed serving different purposes. This has contributed to the industry as we know it today.

To meet today’s statutory requirements and to improve efficiency, the maritime industry is adopting a combination of different power sources (hybrid) such as those found in other sectors. For example, in the automotive industry, hybrid vehicles, and their definition, are already widely spread. Based on Official Journal of the European Union (2017) and UN Economic and Social Council (2015) a hybrid vehicle is defined as “[…] a vehicle equipped with a powertrain containing at least two different categories of propulsion energy converters and at least two different categories of propulsion energy storage systems.”

However, the maritime industry faces a different challenge. Unlike the automotive sector's unified approach, maritime hybrid systems suffer from multiple, sometimes conflicting definitions across different organizations, such as those proposed by the American Bureau of Shipping (2017) and Lloyd's Register (2019). This variety of definitions has prompted discussions within the CIMAC organization, highlighting the urgent need for a clear and unified definition of maritime hybrid systems.

In contrast to that, the number and the differences among existing hybrid system definitions in the maritime industry, such as American Bureau of Shipping (2017) or Lloyd’s Register (2019), in the light of the discussions within the CIMAC organization have revealed the demand for a clear and unified definition of a hybrid system.

Despite this definitional complexity, the term 'hybrid' is extensively used in the maritime sector. Classification authorities have already established classification requirements for hybrid vessels, providing special notations for vessels utilizing different energy sources. Most classification authorities converge on the definition that one of the available energy sources must be electric power or electric storage systems. Three representative examples are presented below:

RINA CLASS (RINA S.p.A., 2025):

> *“Hybrid propulsion system: a propulsion system having two or more different sources of power such as mechanically transmitted power from internal combustion engines, electrical power or hydraulic power so arranged that the ship may be propelled by using the different power sources both separately and in combination (in case the system only allows the separate use, the notation "AVM-APS" will be considered).”*

LLOYDS REGISTER (Lloyd's Register, 2019):

> *“Hybrid Power: Assigned to ships with an electrical power system including a combination of two or more different types of power source or utilising stored electrical energy to satisfy the ship’s main power demand. The system and its component parts are in accordance with the existing applicable requirements of the Rules and the requirements of Pt 6, Ch 2, 24 Hybrid electrical power systems.”*

DNV (Det Norske Veritas AS, 2020):

> *“Hybrid vessel where one of the main sources of power is based on EES.”*
>
> *“Hybrid vessel having an operational mode where the vessel is operating on EES power only, with the other main source of power in standby”.*
>
> *“Hybrid vessel using the EES system as a redundant source of power for main and/ or additional class notations, e.g. dynamic positioning.”*

While classification authorities agree on the requirement for electrical power or electric storage systems, their definitions differ noticeably in specific details. This heterogeneity has created challenges for system integrators, ship owners and operators, classification societies, and regulatory authorities, making a unified hybrid system definition valuable for the entire industry. For this reason, CIMAC WG 20 proposes the herein presented hybrid definition which intends to answer the question 'when is a system actually a hybrid propulsion (or power) system, and when is it not'?

2 CIMAC Hybrid Definition

2.1 Hybrid Definition

There are multiple features that may help describing a hybrid system[1], such as the existence of an energy storage system or the use of alternative energy sources, but, according to the findings in CIMAC Working Group 20, there should be only one general attribute classifying a hybrid system, which is:

> **"The ability to perform a specific function (power production or propulsion) based upon at least two different and independent technologies"**

Please note: Since the word 'hybrid' is a generic term and can describe almost any combination of things, this definition applies to two specific functions only – power production or propulsion. Focusing on the intended function of the system is necessary for setting a reference to clearly describe what the hybrid system and, particularly, its components and technologies are used for.

Without such reference and without further clarification conventional system topologies such as a two-stroke main engine directly connected to the propeller shaft plus a number of auxiliary engines and generators may already suffice the definition of hybrid.[2]Apart from focusing on one specific function, there are two requirements that the system components or technologies have to fulfil. They must be 'different' and 'independent'. These attributes are not unambiguous and need a further detailed explanation, as given below.

2.1.1 Supporting Definition 'Different'

According to the Webster dictionary the term 'different' is defined as 'partly or totally unlike in nature, form, or quality'. Within the scope of this paper the definition of 'different' shall be further restricted to the actual core energy conversion process of a particular propulsion or power production technology, this means: *Two or more systems are different from each other if their underlying core energy conversion processes are different.*

It is argued that by focusing on the core energy conversion process

1. unnecessary energy conversion processes shall be ignored and
2. a suitable degree of separation between two technologies may be achieved.

For instance, 'fuel energy' would fall in the category of chemical energy. Thus, a vessel may not be labeled hybrid just by using two different types of fuel. Admittedly, this is a rather simple example whereas the unambiguous distinction of two fairly similar technologies might be much more difficult and leave room for uncertainty and arguments. Therefore, this paper proposes a scheme for clear differentiation of technologies which shall be introduced using a system configuration commonly accepted as hybrid (see Figure 1).

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[1] System as defined in chapter 2.1.3

[2] There are two different technologies ('internal combustion engine' vs. 'internal combustion engine + generator') that can operate independently from each other. However, in this case the technologies are serving two different functions, that are power generation and propulsion.

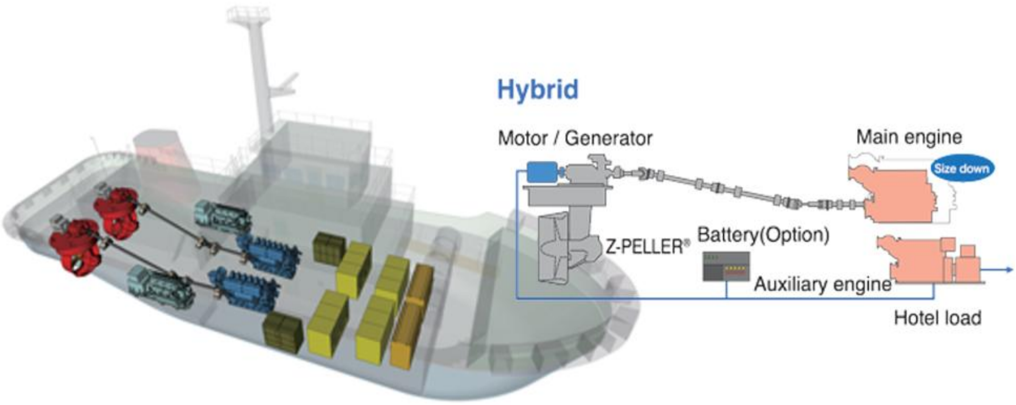

Figure 1: Exemplary 'typical' hybrid system based on (Hybrid tug system. (n.d.))

Correspondingly, in Figure 2 a possible representation of the core energy conversion of the internal combustion engine (which is directly attached to the propeller shaft) is depicted. Fuel as chemical energy, which is classified as thermal and (microscopic) internal energy, is converted – via the energy transfer mechanisms of heat (via combustion) and work – to translational energy (piston movement), which is classified as mechanical and (macroscopic) kinetic energy. Consequently, this energy is converted to rotational energy through the crank-slider kinematics. Eventually, this rotational energy serves the function of propulsion by driving the ship propeller. It shall be stressed that only the main or, respectively, core energy conversion process is monitored – any potential side energy conversion flow, for instance, into waste heat is neglected. Furthermore, the whole energy conversion process can be described by an acronym which allows for easy comparison and display. In fact, in most cases the black capital letters should already provide sufficient classification (see also appendix A.1).

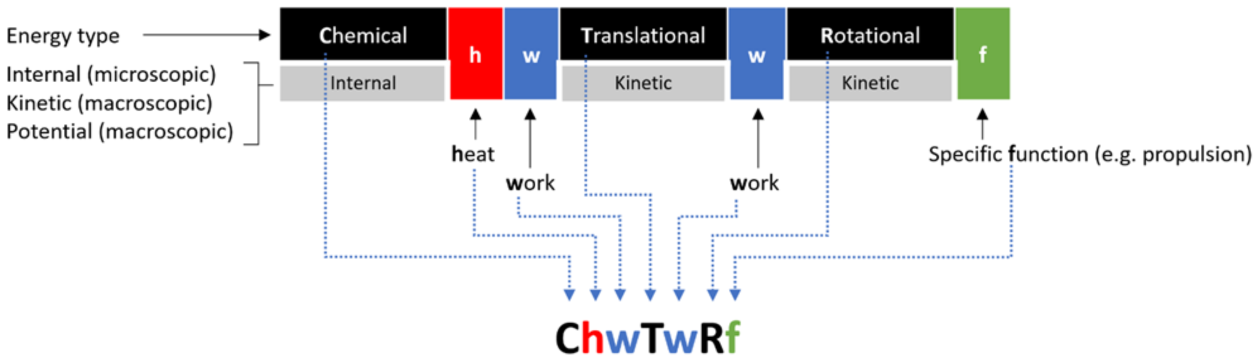

Figure 2: Core energy conversion process of the internal combustion engine

The core energy conversion process of the second part of the system is outlined in Figure 3. Since the system comprises only a battery and an electrical motor the energy conversion can easily be determined: The (potential) electrical energy that is stored in the battery is translated into rotational energy by the motor. Whether a mechanical transmission is attached or not would not make any difference as this would not add any additional energy conversion process. Comparing the two energy conversion flows in Figure 2 and Figure 3 it is evident that the technologies are different.

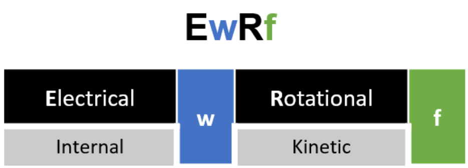

Figure 3: Core energy conversion process of the battery and electric motor

Another example for illustrating the definition of 'different' is shown below (see Figure 4). For the sake of clarity, the potential hybrid propulsion plant is separated into the two sub-systems A and B.

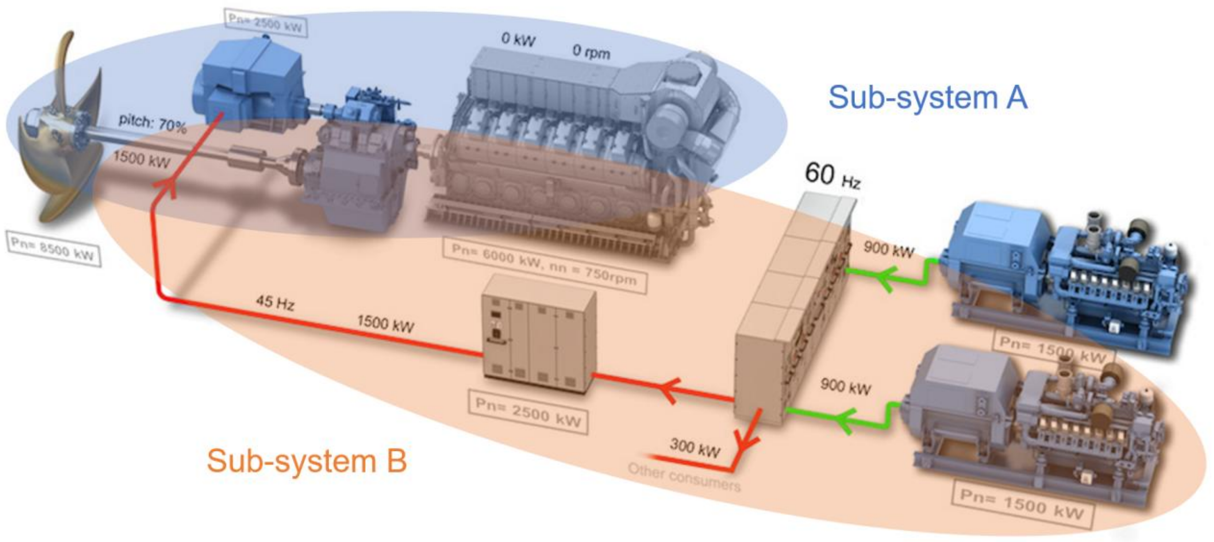

Figure 4: (Sub)Systems of a hybrid ship propulsion plant, based on (illustration based on Hybrid or electric ship propulsion. (n.d.))

Drawing the energy conversion flow for each sub-system will result in two more or less similar representations: As depicted in Figure 5, both processes emerge from an internal combustion engine and end on the propeller shaft. In between the energy is converted mechanically (in sub-system A), or mechanically and electrically (in sub-system B). It should be noted that both energy flows differ only by the existence of an 'electrical transmission'. Such 'electrical transmission', however, is necessary for the sake of power distribution and, thus, an eligible part of the core energy conversion process. In that case, both sub-systems are different according to this definition.

CTRRR ≠ **CTRREEERR**

Sub-system A	System component	Energy type
Starting point	Fuel tank/Other	Chemical
Stage 1	Main engine	Translational
Stage 2	Main engine	Rotational
Stage 3	Gearbox	Rotational
Stage 4 (ship propulsion)	Propeller	Rotational

Sub-system B	System component	Energy type
Starting point	Fuel tank/Other	Chemical
Stage 1	Auxiliary ICE	Translational
Stage 2	Auxiliary ICE	Rotational
Stage 3	Gearbox	Rotational
Stage 4	Auxiliary Generator	Electrical
Stage 5	Switchboard	Electrical
Stage 6	Generator/Motor	Electrical
Stage 7	Gearbox	Rotational
Stage 8	Propeller	Rotational

Figure 5: Energy conversion processes for sub-system A and B

2.1.2 Supporting Definition ‘Independent’

Apart from having a system with two different technologies, another criterion is suggested to complement the definition of a hybrid system: Independence. Theoretically it would be possible to design a system containing two different technologies that may serve one specific function whereas one technology could contribute only marginally to this function – would such a system be deemed hybrid?

In fact, the presented hybrid definition does not specify the required degree of hybridization or allows for any declaration of the ‘sizing’ of the technologies. Such declaration would arguably require a high level of detail (e.g. battery size/type, shaft generator power/type, max. wind assistance, etc.) which, in turn, would have to be determined for each vessel type, i.e. from small tugboats over shuttle tankers to large container vessels. Apart from the immense effort of finding such universal hybrid classification – i.e. for all vessel types, present and future technologies, component sizing and topologies – it is also questionable whether the increase of complexity will add enough value to outweigh the anticipated decrease of applicability of the definition.

For this reason, the supporting definition of ‘independent’ has been formulated as: *An independent system contains two or more technologies that are capable of operating independently from each other while serving the intended specific function (i.e. propulsion or power production). The specific function has to be fulfilled even in case the other hybrid technology is currently not available.*

It is argued that by adding the aspect of independence to the hybrid definition:

1. only reasonably[3] sized technologies will allow for classification as hybrid
2. Both technologies have to be capable of independently serving the intended function. Note that if the energy sources are intermittent, a careful assessment is required to ensure that the intended function can be reliably maintained at all times.
3. The responsibility for determining the required sizing of the hybrid components – ensuring each technology can operate independently – and the duration for which the intended function must be maintained is delegated to the system or vessel owner, or client.

In other words, the herein proposed hybrid definition will deliver the framework for what, in principle, can be considered a hybrid system. Whether the technology itself actually suffices the requirement of independently serving the specific function (i.e. to which extent and for how long) is yet to be decided by the client.[4]

2.1.3 System and System Boundaries

A ‘system’ is defined as ‘a combination of interacting elements organized to achieve one or more stated purposes’ according to International Organization for Standardization (ISO, 2015). Boundaries of the hybrid system will need to be derived by the relevant stakeholders[5] and can cover hardware elements (e.g. engines, batteries, converters, etc.), software elements (e.g. control, safety, monitoring, etc.), process and procedures.

2.1.4 Technologies

According to (ISO, 2013) technology is defined as the “application of scientific knowledge, tools, techniques, crafts, systems or methods of organization in order to solve a problem or achieve an objective”. For the sake of this hybrid system definition, it is important to note that the focus is here set on the ‘application of systems’ and that these systems, in turn, have to be capable of converting energy.

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[3] There is not a clear definition of a reasonably sized technology however it should be understandable that a battery capacity in the range of <1 kWh may be sufficient for cranking up a passenger car but not for propelling a container ship.

[4] Where a customer requirement is defined as 'No single point event should result in an intolerable risk, the design of the 'system' should consider potential common cause/mode failures e.g. single fuel tanks.

[5] We conclude that the requirements for the system boundaries are to be specified by the hybrid system client (e.g. ship owner, regulators, naval architects, shipyard, etc.).

2.1.5 Discussion on Distinction from Existing Definitions

Given that an established definition of hybrid vehicles already exists (UN Economic and Social Council, 2015), it is worth examining why CIMAC proposes a distinct definition for the maritime industry. A comparison of the UN Economic and Social Council (2015) definition with CIMAC's proposal reveals several key differences that justify this maritime-specific approach.

While the two definitions share similarities, they differ in three important aspects:

- **System Integration and Function:** Vehicle powertrains typically serve a single primary function: propulsion (aside from auxiliary generators). In contrast, hybridized ship propulsion systems become deeply integrated with the vessel's overall operation, interconnecting with economizers, steam production, waste heat recovery systems, and auxiliary generator sets. Ship propulsion systems more closely resemble powerplants in their complexity and interconnectedness. Therefore, hybrid maritime systems require a clear distinction between their intended functions—whether for propulsion or power generation.

- **Technology Scope and Flexibility:** The maritime industry employs diverse technologies for propulsion and power production. Restricting the definition to predetermined categories such as internal combustion engines, electric machines, and fuel cells would be inappropriately limiting. Maritime systems may incorporate technologies ranging from nuclear powerplants to conventional diesel engines, wind-assisted propulsion, solar power systems, and various combinations thereof. CIMAC's approach addresses this complexity by focusing on higher-level principles and defining technologies through supporting concepts of "independent" and "different" systems.

- **Safety and Redundancy Considerations:** Automotive definitions typically use the term "propulsion energy converter" and narrow their scope through requirements like "using output energy directly or indirectly for vehicle propulsion" or excluding "peripheral devices." CIMAC's proposal addresses this through the requirement of at least two "independent" technologies. This approach reflects the maritime industry's emphasis on redundancy and safety, potentially leading to a more safety-focused understanding of hybrid systems in marine applications.

2.2 Hybrid System Characterization

This section shall provide a systematic assessment of whether a system is considered hybrid according to the CIMAC definition. In this respect, Figure 6 presents a flowchart for applying the Maritime Hybrid Systems definition established in this paper. The classification follows a three-stage decision tree that determines whether a maritime propulsion system qualifies as hybrid. Each stage represents a critical criterion that must be satisfied to achieve hybrid classification.

- The first stage assesses whether all technologies serve the same specific function (either propulsion or power production). Systems where technologies serve different functions are excluded from hybrid classification.
- The second stage evaluates technological differentiation, ensuring that constituent technologies employ fundamentally different core energy conversion processes rather than duplicating identical technologies. For example, twin main engines in a vessel with twin skeg design fail this criterion.
- The final stage evaluates operational independence, requiring that each technology can autonomously fulfill the intended function without reliance on the other. Systems where one technology depends on another for core functionality, or where neither technology can fulfil the intended function independently, are excluded at this stage.

Only systems satisfying all three criteria achieve "Hybrid Propulsion System" classification, demonstrating functional equivalence, technological diversity, and operational independence. This framework eliminates classification ambiguity and ensures that only systems exhibiting true hybrid characteristics receive the hybrid designation.

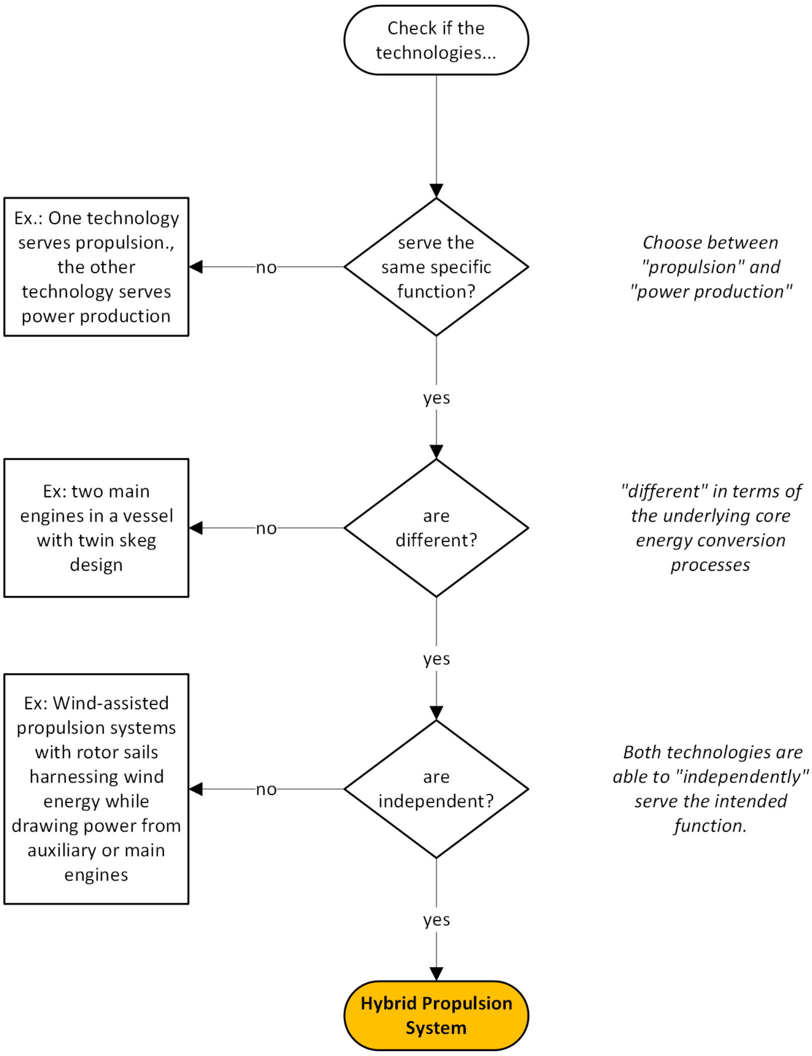

Figure 6: Simplified flowchart for definition of a Maritime Hybrid System

3 Examples

In order to develop an intuition for applying the CIMAC hybrid definition, this chapter shall discuss some examples for what is deemed a hybrid and a non-hybrid configuration.

3.1 Hybrid and Non-hybrid Systems

In addition to previously discussed example, further system configurations shall be assessed with respect to the criteria of the proposed hybrid definition. Please note that the classification strongly depends on the details of each configuration (as they are outlined in the 'Description' field). For instance, a 'Diesel + SG' configuration may also be classified 'non-hybrid' in case the electric motor is not powerful enough or does not provide a PTI functionality.

Table 1: Examples of hybrid and non-hybrid system types

System	Description	SF	DIFF	IND	Hybrid
Internal Combustion Engine (ICE) + Shaft generator (SG)	Ship propulsion by ME or via PTI function of the SG. PTI is powerful enough to propel the ship. AE deliver power for PTI.	prop.	yes	yes	**yes**
ICE + Battery	Mild Hybrid - diesel and batteries always run together. These plants cannot run in pure electrical mode. Two forms of power generation but no redundancy.	prop.	yes	no	**no**
ICE + Battery	Two different energy conversion processes while the intended function is power production. I.e. either the battery or the SG, and the AE will provide power for hotel load. Battery and SG are suitably sized to replace an AE.	pow. prod.	yes	yes	**yes**
ICE + Battery	FHEV - can run on the diesel engine, the batteries/electric drive or a combination of both.	prop.	yes	yes	**yes**
FC + Battery	Fuel cells supplied by hydrogen tank. Battery sizing/capacity is sufficient for independently propelling the ship.	prop.	yes	yes	**yes**
Nuclear + Power Take-in (PTI) + Battery	Steam generator supplied by nuclear power. Steam turbine propels ship. Another steam turbine generates power to be stored in the battery. Battery and PTI are sized to independently propel the ship.	prop.	yes	yes	**yes**
COmbined Gas turbine Electric and Steam (COGES)	Combined gas turbine and steam turbine integrated electric drive system. This arrangement uses two forms of energy for propulsion and power generation	prop.	no	yes	**no**

AE	Auxiliary engine
COGES	Combined gas turbine electric and steam system
DIFF	Different: Are the technologies different?
FHEV	Full hybrid electric vehicle
ICE	Internal Combustion Engine
IND	Independent: Are the technologies independent?
ME	Main engine
PTI	Power take-in
SF	Specific function: Serving the same specific function?
SG	Shaft generator

3.1.1 Hybrid Definition Example: IHI Tugboat

In (Shiraishi et al., 2013) Japan’s first hybrid tugboat is described, designed to improve energy efficiency and reduce emissions. Its propulsion system combines a main diesel engine (2 × 1800 PS / 1323 kW), an electric motor/generator (400 PS / 294 kW), a diesel generator (400 kW), and a lithium-ion battery bank (150 kWh). The hybrid tugboat operates in two distinct modes. In transit mode, when the propeller speed is below the “setting speed,” the clutch is disengaged and propulsion is provided solely by the electric motor, powered by the battery, with the main engine stopped or idling. Once the propeller speed rises above the setting speed, the clutch engages, and the system enters the hybrid range, where propulsion is delivered by both the main engine and the motor. In working mode (bollard-pull operations), the tugboat is driven primarily by the main engine, while the motor provides additional torque. The hybrid setup enabled approximately 20% reductions in fuel consumption and CO_2, emissions compared to conventional tugboats.

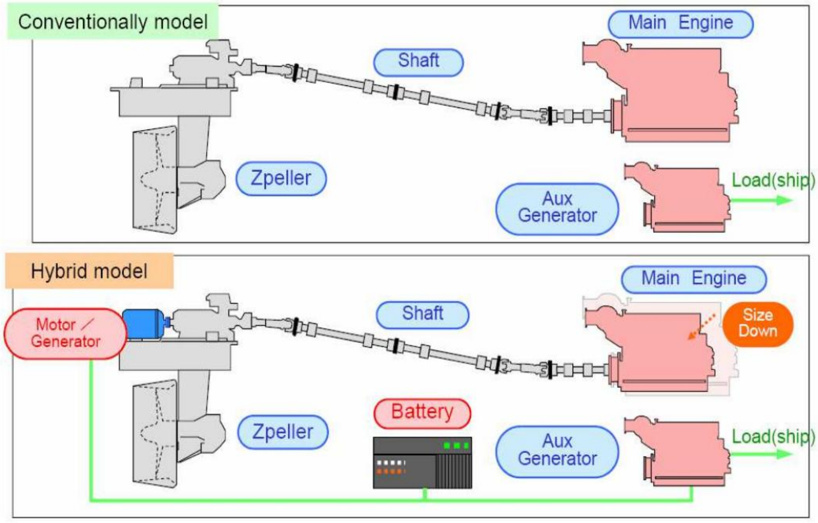

Figure 7: IHI tugboat hybrid propulsion system (Shiraishi et al., 2013)

According to the proposed CIMAC hybrid definition, this tugboat clearly qualifies as a hybrid vessel. Propulsion can be provided either by the diesel engine or by the electric motor powered from batteries/diesel generator, two independent technologies capable of working separately or in parallel.

3.2 Wind assisted propulsion

Shipping propulsion by wind is one of the oldest technologies in use for all kind of vessels. With the occurrence of mechanical propulsion by steam and Diesel engines and the ability, to be independent from wind direction and force, this technology disappeared at least for cargo vessels. Since several years the combination of mechanical propulsion with wind usage is discussed as possibility to reduce fuel consumption and emissions.

3.2.1 Introduction of WAPS technologies

Wind-assisted propulsion technologies (WAPS) use wind power to produce additional propulsion power, which opens the possibility to reduce fuel consumption and greenhouse gas emissions in commercial shipping. These systems supplement conventional engines and include several main types (see following examples):

- Rotor Sails (Flettner Rotors): Spinning vertical cylinders that create thrust via the Magnus effect when wind flows across them.
- Rigid Sails / Wing Sails: Fixed or semi-rigid aerofoil-shaped structures that act like aircraft wings to generate lift and propel the ship.
- Soft Sails: Traditional or modernized fabric sails, sometimes automated, used to harness wind in a more flexible and lightweight setup.
- Kites (Towing Kites): Large, computer-controlled kites deployed from the bow of a ship that capture strong, high-altitude winds.
- Suction Wings (Turbosails): Aerofoils with internal fans that enhance airflow, increasing lift and propulsion.

3.2.2 WG20 View on Maritime Hybrid and WAPS Definitions

The current definition of maritime hybrid systems emphasizes the use of *different* and *independent* technologies, each of which must be individually capable of performing the intended function. The WAPS propulsion effect though depends on the availability of the energy source 'wind' and the corresponding wind direction – due to its intermittent nature of this energy source, however, WAPS do not suffice the sub definition criterion of independence. Consequently, WAPS can only fulfill a supporting role in propulsion – a view that aligns closely with how classification societies commonly define wind-assisted propulsion systems. A review of selected definitions clearly shows that wind technology is generally considered a supplementary contributor to the primary function of propulsion:

- According to DNV (n.d.), “These technologies harness the power of wind to supplement the propulsion of a vessel by generation of aerodynamic force”
- American Bureau of Shipping (2022) defines WAPS as: “Wind Assisted Propulsion System. An assembly leveraging wind energy for generating thrust force to assist the propulsion of a ship. It includes supporting structure members, thrust generating members, and drive system.”
- Lloyd’s Register (2024) is even more explicit regarding the supportive nature of wind propulsion: “wind assisted propulsion system, referring to sails or other wind propulsion generating devices and systems which are not intended as the primary means of propulsion.”

Accordingly, in the context of WAPS, the CIMAC WG20 definition of maritime hybrid systems is well aligned with the current consensus among classification societies.

3.2.3 WAPS Example: E-Ship1

According to Wikipedia (“E-Ship 1,” n.d.), the *E-Ship 1* is a roll-on/lift-off (RoLo) cargo vessel operated by the German wind turbine manufacturer Enercon (see Figure 8). The vessel is equipped with four rotor sails – also referred to as Flettner rotors – each measuring 27 meters in height and 4 meters in diameter. Notably, the Flettner rotors are driven by a steam turbine that utilizes waste heat from the main diesel generators. This configuration inherently creates a dependency between the two technologies, as the operation of the rotors relies on the availability of sufficient exhaust heat from the main engines to power the steam turbine.[6]

Figure 8: Example of a wind assisted propulsion technology [Die E-Ship 1 *im Emder Hafen]*

Using the framework introduced in the previous chapters, the case can be analyzed as follows: The vessel employs two distinct technologies – an internal combustion engine and rotor sails – as part of a potential hybrid system. Both technologies differ in their core energy conversion processes and serve the same specific function: propulsion. However, the rotor sails cannot fulfill this function independently. Wind propulsion is limited by the intermittency of the wind, and in this case, the operability of the Flettner rotors additionally depends on waste heat from the main engine. Therefore, the vessel does not meet the criteria for classification as a hybrid propulsion system as defined in this paper.

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[6] This interdependence alone precludes classification as a hybrid propulsion system according to the criteria established in this paper.

4 Conclusion

The paper addresses the apparent ambiguity created by the existence of multiple hybrid system definitions across various classification societies in the maritime industry. CIMAC Working Group 20 proposes a unified, clear definition to resolve this fragmentation.

CIMAC's Hybrid Definition:

"The ability to perform a specific function (power production or propulsion) based upon at least two different and independent technologies"

Key clarifications are:

- "Different" - Technologies must have distinct core energy conversion processes (not just different fuels or minor variations)
- "Independent" - Each technology must be capable of operating independently to fulfill the intended function, even when the other technology is unavailable
- Specific Function - The definition applies to two distinct functions: propulsion OR power production

The paper provides a systematic framework for determining whether a system qualifies as "hybrid," moving beyond the current industry confusion where multiple definitions exist. This unified approach supports system integrators, ship owners, classification societies, and authorities by establishing clear criteria.

Apart from that, the definition excludes systems where one technology merely assists another (like most Wind-Assisted Propulsion Systems) and requires genuine redundancy and independence between technologies. This creates a more stringent but clearer standard that emphasizes safety and reliability - core maritime industry values.

5 List of Abbreviations

AE	Auxiliary Engine
CIMAC	International Council on Combustion Engines
COGES	Combined Gas Turbine and Steam Turbine Integrated Electric Drive System
DIFF	Different
DNV	Det Norske Veritas
FC	Fuel Cell
FHEV	Full Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IND	Independent
ISO	International Organization for Standardization
ME	Main Engine
PTI	Power Take-In
RoLo	Roll-on/Lift-off
SF	Specific Function
SG	Shaft Generator
UN	United Nations
WAPS	Wind-Assisted Propulsion System/Technologies
WG	Working Group

6 Glossary

Core Energy Conversion Process

The fundamental energy transformation mechanism of a technology, focusing on the primary energy conversion pathway while ignoring secondary processes like waste heat generation.

Different Technologies

Two or more systems are considered different if their underlying core energy conversion processes are fundamentally distinct in nature, form, or quality.

Energy Conversion

The process of transforming energy from one form to another (e.g., chemical to mechanical, electrical to rotational) through mechanisms of work and/or heat transfer.

Flettner Rotor

A spinning vertical cylinder that creates thrust via the Magnus effect when wind flows across it, used as a wind-assisted propulsion technology.

Hybrid System

A system with the ability to perform a specific function (power production or propulsion) based upon at least two different and independent technologies.

Independent Technologies

Technologies that are capable of operating independently from each other while serving the intended specific function, even when other hybrid technologies are not available.

Magnus Effect

The physical phenomenon where a spinning cylinder in a moving airstream experiences a force perpendicular to the direction of the airstream, used in Flettner rotors for propulsion.

Power Production

One of two specific functions covered by the hybrid definition, referring to the generation of electrical or mechanical power for ship operations (excluding propulsion).

Power Take-In (PTI)

A system that allows an electric motor/generator to operate as a motor, using electrical power to provide mechanical propulsion to the shaft.

Propulsion

One of two specific functions covered by the hybrid definition, referring to the generation of thrust or driving force to move the vessel through water.

Shaft Generator (SG)

An electric generator connected to the main propulsion shaft that can generate electrical power and, in PTI mode, provide propulsion power.

Specific Function

The intended primary purpose of a system, limited to either propulsion or power production in the context of maritime hybrid systems.

System

A combination of interacting elements (hardware, software, processes, procedures) organized to achieve one or more stated purposes.

System Boundaries

The defined limits of what components, processes, and procedures are included within the hybrid system scope, determined by relevant stakeholders.

Technology

The application of scientific knowledge, tools, techniques, or systems capable of converting energy to solve a problem or achieve an objective.

Wind-Assisted Propulsion System (WAPS)

Technologies that use wind power to supplement conventional propulsion, including rotor sails, rigid sails, soft sails, kites, and suction wings.

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A Appendix

A.1 Energy Forms

This Appendix presents classifications of energy forms as used in the presented CIMAC Hybrid Definition paper. Engineering, macroscopic-scale classification is emphasized here since it is the most relevant in marine engineering systems (Woud & Stapersma, 2022; Powers, 2023). For consistency, however, a brief account of microscopic-scale classification based on modern physics concepts is also given. For the sake of simplicity, we further distinguish not between kinetic and potential microscopic energy but rather group it all together under “internal energy” (as can be seen in Figure 9).

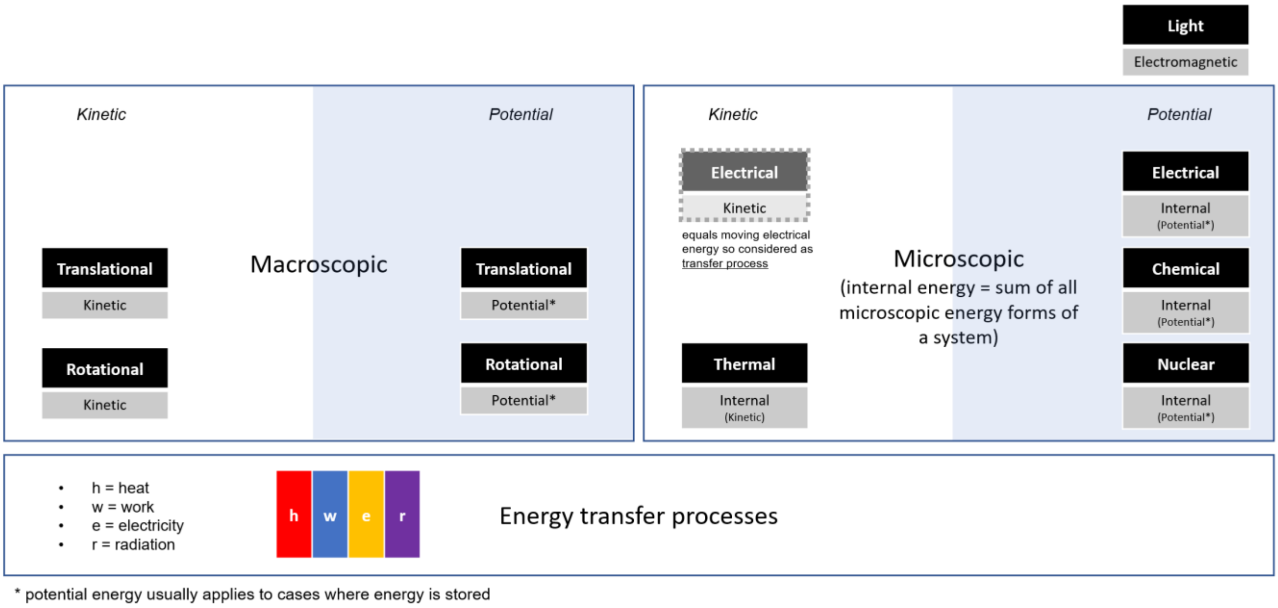

Figure 9: Overview of Energy Forms

As has been seen in the main text, energy forms in macroscopic scales that are employed to explain and understand hybrid as well as non-hybrid power and propulsion plants in marine engineering include predominantly the following:

- *kinetic energy* as it arises e.g., in rotational motion of rotors or propellers and in translational reciprocating motion in piston engines like diesels
- *mechanical work* produced by engines and motors
- *internal energy* mainly stored in the form of chemical bonds in fuels like hydrocarbons or in batteries used in the shipping industry
- *heat* as an undesirable byproduct in many processes used in the maritime industry due to e.g., friction but also as the indispensable intermediary to produce work in heat engines
- *electrical energy* provided by generators or batteries shipboard and required in order to run e.g., electric motors onboard vessels outfitted with electric propulsion.

More details about the nature and the physics involved in the energy forms arising in marine engineering including the ones mentioned in this paragraph, follow.

A.2 Energy Forms in Macroscopic Scales

The most important energy forms in marine engineering systems are those arising in macroscopic scales and they include the following broad categories (Woud & Stapersma, 2022):

A.2.1 Work and Mechanical Energy

Work is energy transferred to or from an object via the application of force along a displacement (Woud & Stapersma, 2022; Powers, 2023). Work can be performed on objects experiencing translational motion in which case it is defined as the line integral below.

$$W = \int_{x_1}^{x_2} \boldsymbol{F} \cdot d\boldsymbol{x}$$

In the case, where work is performed on objects experiencing rotational motion the torque can be used instead as follows to calculate the work along an arc.

$$W = \int_{x_1}^{x_2} \boldsymbol{F} \cdot d\boldsymbol{x} = \int_{\vartheta_1}^{\vartheta_2} F_{\vartheta} r \, d\vartheta = \int_{\vartheta_1}^{\vartheta_2} M \, d\vartheta$$

Mechanical energy is the sum of mechanical potential energy plus kinetic energy (Blank et al., 1985; Woodyard, 2009). Kinetic energy is a form of energy that an object or a particle has by reason of its motion. If work, which transfers energy, is done on an object by applying a net force, the object speeds up and thereby gains kinetic energy. This is how the well-known equation for translational kinetic energy of a moving object can be obtained, by employing Newton's second law of motion.

$$E_{KIN} = \int_0^x \boldsymbol{F} \cdot d\boldsymbol{x} = \int_0^t m\boldsymbol{a} \cdot \boldsymbol{v} dt = \int_0^t m \frac{d\boldsymbol{v}}{dt} \cdot \boldsymbol{v} dt = \int_0^v m\boldsymbol{v} \cdot d\boldsymbol{v} = \frac{1}{2} m v^2$$

A similar equation holds for the rotational kinetic energy of a rotating object, where the mass has been replaced by moment of inertia about the axis of rotation and the velocity with angular velocity in radians per second.

$$E_{rot} = \frac{1}{2} I \omega^2$$

Mechanical potential energy arising in marine engineering systems is commonly due to either gravity or elasticity. For gravity, assuming constant gravitational acceleration for simplicity, the potential energy is calculated as the work of the weight.

$$E_{gravity} = \int_0^z \boldsymbol{F} \cdot d\boldsymbol{x} = \int_0^z m\boldsymbol{g} \cdot d\boldsymbol{x} = mg \int_0^z dx = mgz$$

The potential energy of a lumped spring due to the elasticity of its material is also calculated as the work of the restoring force a linear (aka with restoring force proportional to deformation) spring exerts when externally stretched or compressed.

$$E_{spring} = \int_0^x \boldsymbol{F} \cdot d\boldsymbol{x} = \int_0^x kx \, dx = k \int_0^x x \, dx = \frac{1}{2} k x^2$$

A.2.2 Thermal Energy

Thermal energy in marine engineering systems arises in three major modes: Internal energy, enthalpy and heat. Internal energy is divided into two components (Powers, 2023; Blank et al., 1985; Woodyard, 2009): microscopic potential energy and microscopic kinetic energy. The microscopic kinetic energy of a system arises as the sum of the kinetic energies due to motion of all the system's particles with respect to the center-of-mass frame. The microscopic potential energy algebraic summation components are those of the chemical and nuclear particle bonds, and the physical force fields within the system, such as due to internal induced electric or magnetic dipole moment, as well as the energy of deformation of solids (stress-strain). Usually, the split into microscopic kinetic and microscopic potential energy is outside the scope of macroscopic thermodynamics and typically arises in considerations related to statistical mechanics. For an ideal gas, the internal energy can be obtained as follows.

$$U = mu, u = c_V T \Rightarrow du = c_V\, dT$$

It is reminded that an ideal gas is a gas for which the following state equation holds.

$$pV = mRT \underset{\rho=m/V}{\Longleftrightarrow} p = \rho RT \underset{v=1/\rho}{\Longleftrightarrow} pv = RT \Rightarrow p\, dv + v\, dp = R\, dT \Rightarrow \frac{dv}{v} + \frac{dp}{p} = \frac{dT}{T}$$

Enthalpy is the sum of a system's internal energy and the product of its pressure times its volume. The pressure–volume term expresses the work required to establish the system's physical dimensions, i.e. to make room for it by displacing its surroundings. In the case of an ideal gas:

$$H = mh, h = u + pv \Rightarrow dh = du + (p\, dv + v\, dp) = c_V\, dT + R\, dT = c_p\, dT$$

Enthalpy and internal energy are also related by the following fundamental equation of thermodynamics to the state variable of entropy.

$$T\, dS = dU + p\, dV = dU + p\, dV + V\, dp - V\, dp = dH - V\, dp$$

Heat is energy in transfer to or from a thermodynamic system, by mechanisms other than work or transfer of matter. The mechanisms of energy transfer that define heat include conduction, through direct contact of immobile bodies, or through a wall or barrier that is impermeable to matter; or radiation between separated bodies; or friction due to isochoric mechanical or electrical or magnetic or gravitational work done by the surroundings on the system of interest. When there is a suitable path between two systems with different temperatures, heat transfer occurs necessarily, immediately, and spontaneously from the hotter to the colder system. Convection is the transfer of heat from one place to another due to the movement of mass, typically fluid. Although often discussed as a distinct method of heat transfer, convective heat transfer involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). Convection is usually the dominant form of heat transfer in liquids and gases. Heat is connected to enthalpy, internal energy, work and mechanical energy by the first law of thermodynamics which for a control volume with a single mass inlet and single mass outlet obtains the following form.

$$\left.\begin{aligned} \frac{dm_{vol}}{dt} &= \dot{m}_i - \dot{m}_o \\ \frac{dE_{vol}}{dt} &= \dot{Q} - \dot{W} + \dot{m}_i\left(h_i + \frac{v_i^2}{2} + gz_i\right) - \dot{m}_o\left(h_o + \frac{v_o^2}{2} + gz_o\right) \end{aligned}\right\}$$

In the above, the first equation is mass balance while the second equation is the energy balance for the control volume at hand.

For a control volume that is an open system with incompressible fluid flow at steady state (a situation commonly arising in marine engineering practice) it holds that:

$$\frac{dm_{vol}}{dt} = 0 \Rightarrow \dot{m}_i = \dot{m}_o = \rho\dot{V}, \frac{dE_{vol}}{dt} = 0$$

In result, the energy balance equation of the first law of thermodynamics becomes the Bernoulli equation as follows.

$$\mathrm{h_{PUMP}} - \mathrm{h_{loss}} = \frac{p_o - p_i}{\rho g} + (z_o - z_i) + \frac{v_o^2 - v_i^2}{2g}$$

In the above, the pump head represents the energy added to the fluid by the work produced by a pump sustaining the flow and the head loss the energy removed as heat from the fluid by friction or viscous losses as it passes through the control volume. Notice that passing through the control volume is assumed to cause negligible (if not zero) change in internal energy of the fluid, since typically temperature does not change significantly. In Bernoulli's equation the first two terms on the right-hand side represent the static pressure (the second being hydrostatic pressure) and the last term the dynamic pressure.

$$\mathrm{h_{PUMP}} = -\frac{\dot{W}}{\rho g \dot{V}} \geq 0,\ \mathrm{h_{loss}} = -\frac{\dot{Q}}{\rho g \dot{V}} \geq 0$$

For a closed (aka without mass flow in or out) thermodynamic system, we obtain the following by applying the first law of thermodynamics.

$$\frac{dm_{vol}}{dt} = \dot{m}_i = \dot{m}_o = 0 \Rightarrow \delta Q = dU + \delta W$$

The second law of thermodynamics requires that heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time. As a consequence of the second law, for a closed system it holds that

$$dS \geq \frac{\delta Q}{T_{surr}}$$

The equality holds for an idealized closed system undergoing a reversible process while the inequality holds for a closed system undergoing the actually possible, irreversible process. If the process is also adiabatic (i.e. $\delta Q = 0$) then the above results in $\Delta S \geq 0$.

A.2.3 Electrical Energy

Electrical energy is derived as a result of movement of electrically charged particles (Patel, 2021; Patel, 2012; Giurgiutiu & Lyshevski, 2016). Electrical energy refers to energy that has been converted from electric potential energy.

$$W_e = \int_{\infty}^{x} \boldsymbol{F} \cdot d\boldsymbol{x} = q \int_{\infty}^{x} \mathbf{E} \cdot d\boldsymbol{x} = \mathrm{U}(\boldsymbol{x}) \Rightarrow \Delta\mathrm{U} = \mathrm{U}(\boldsymbol{x}_2) - \mathrm{U}(\boldsymbol{x}_1)$$

This energy is supplied by the combination of electric current (amperage) and voltage (potential difference) that is delivered by an electric circuit. In this case, instantaneous electric power is the product of the voltage times the amperage and determines the instantaneous rate by which electrical energy is transferred to or from a circuit element or subcircuit:

$$\mathrm{p}(t) = \mathrm{v}(t)\, i(t)$$

Notice that even though energy of electrostatic fields and magnetostatic fields by permanent magnets is potential, electromagnetic field energy is not, in general, potential energy because fields in electrodynamics are nonconservative, i.e. not irrotational. With this in mind, the voltage in electric circuits is an appropriate generalization that can include even nonconservative cases (when the "voltage" between two points depends on the path taken).

The simplest electrical element is the linear ohmic resistor or equivalently electrical conductance in siemens (mhos). The voltage-current relationships defining the element are given below along with the equations for instantaneous power.

$$\mathrm{v} = \mathrm{R}i, i = G\mathrm{v} \Rightarrow \mathrm{p}(t) = \mathrm{R}i^2 = G\mathrm{v}^2$$

Typically, a resistor converts electric power and energy to heat. The amount of heat generated by a resistor is obtained by the equation below.

$$\Delta E = \int_0^{\tau} \mathrm{p}(t)dt = \int_0^{\tau} \mathrm{v}(t)i(t)dt \underset{\mathrm{DC}}{\Rightarrow} \Delta E = \tau \mathrm{v}i = \tau\mathrm{R}i^2 = \tau\mathrm{v}^2/\mathrm{R}$$

The last equations, hold for a resistor fed by DC (Direct Current, i.e. one-directional flow of electric charge) constant voltage or electric current.

Another circuital element of interest is a capacitor, that acts as storage of electric field energy. To calculate the energy stored in a capacitor we first calculate the electric field between its plates and establish the relationship between the electric charge stored on its plates and the voltage applied across. To achieve this, we start from Gauss' law for the electric field.

$$\oiint_{\partial V} \mathbf{E} \cdot d\mathbf{A} = \frac{\Sigma \mathrm{q}}{\varepsilon_0} \Rightarrow \mathrm{E} = \frac{\mathrm{q_{plate}}}{\varepsilon_0 \mathrm{A}} \Rightarrow \frac{\mathrm{v}}{\ell} = \frac{\mathrm{q_{plate}}}{\varepsilon_0 \mathrm{A}} \Rightarrow \mathrm{q_{plate}} = \mathrm{Cv}, \mathrm{C} = \frac{\varepsilon_0 \mathrm{A}}{\ell}$$

Then, we employ the fundamental equation for electric power which after integration over time yields the electric field energy stored in the capacitor as a function of the voltage across.

$$E_{capacitor} = \int_0^{\tau} \mathrm{p}(t)dt = \int_0^{\tau} \mathrm{v}i\, dt = \int_0^{\tau} \frac{\mathrm{q_{plate}}}{\mathrm{C}} \frac{d\mathrm{q}}{dt}\, dt = \frac{\mathrm{q_{plate}^2}}{2\mathrm{C}} = \frac{1}{2}\, \mathrm{Cv}^2$$

The final idealized element used to model actual electrical or electromechanical systems (besides the resistor and capacitor presented previously) is the inductor which acts as storage of magnetic field energy. To calculate the magnetic energy stored in an inductor, we start by using Ampère's circuital law to obtain the magnetic field at the center of the inductor's solenoid core.

$$\oint_{\partial \mathrm{S}} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0\, \Sigma i + \underbrace{\mu_0 \varepsilon_0 \frac{\partial}{\partial t} \oiint_{\mathrm{S}} \mathbf{E} \cdot d\mathbf{A}}_{\text{0 for practical cases}} \Rightarrow \mathrm{B} = \frac{\mu_0 N i_{\mathrm{L}}}{\ell}$$

We then employ Faraday's law of induction to obtain the inductor's voltage current relationship.

$$\mathrm{v_L} = -\frac{d\Phi_{\mathrm{total}}}{dt} = -N \frac{d}{dt} \iint_{\substack{\text{core}\\\text{cross}\\\text{section}}} \mathbf{B} \cdot d\mathbf{A} = -N \frac{d}{dt}\left(\frac{\mu_0 N i_{\mathrm{L}} \mathrm{A}}{\ell}\right) \Rightarrow \mathrm{v_L} = \mathrm{L}\, \frac{di_{\mathrm{L}}}{dt}, \mathrm{L} = \mu_0 N^2 \frac{\mathrm{A}}{\ell}$$

Finally, we invoke the fundamental equation for electric power, which after integration over time yields the magnetic field energy as function of the electric current through the inductor.

$$E_{inductor} = \int_0^{\tau} \mathrm{p}(t)dt = \int_0^{\tau} i_{\mathrm{L}} \mathrm{v_L}\, dt = \int_0^{\tau} \frac{\Phi_{\mathrm{total}}}{\mathrm{L}} \frac{d\Phi_{\mathrm{total}}}{dt}\, dt = \frac{\Phi_{\mathrm{total}}^2}{2\mathrm{L}} = \frac{1}{2}\, \mathrm{L}\, i_{\mathrm{L}}^2$$

Circuit topologies involving resistors, capacitors and inductors as well as switches and voltage or less commonly electric current sources can be used to model and analyze the operation of the vast majority of ocean and shipboard electric power systems.

Even though DC is gaining support in terms of applications within the maritime industry (Patel, 2021; Patel, 2012), AC (alternating current, an electric current which periodically reverses direction and changes its magnitude continuously with time) with sinusoidal voltage or current sources of at least nominally a single frequency remains a staple in marine electrical practice. For the analysis of single-frequency sinusoidal AC systems the concept of complex power is introduced as follows by using the phasors (i.e. vectors on the complex plane) of the AC voltage and electric current applied to a load or supplied by a source or fed to a subcircuit.

$$\boldsymbol{S} = \mathrm{P} + \mathrm{jQ} = \boldsymbol{V}\boldsymbol{I}^*, \mathrm{j} = \sqrt{-1} \Rightarrow \begin{cases} \mathrm{P\ [W]} = \mathrm{VI}\cos\varphi, \cos\varphi = \mathrm{(PF)} \\ \mathrm{Q\ [var]} = \mathrm{VI}\sin\varphi \\ |\boldsymbol{S}|\ \mathrm{[VA]} = \sqrt{\mathrm{P}^2 + \mathrm{Q}^2} \end{cases}$$

The following terms are used to describe energy flow in a system; note that each power term is assigned a different unit to differentiate between them.

Active power, P, (or real power) in watts (W) or multiples thereof e.g. kW;

Reactive power, Q in volt-ampere reactive (var, but also found as VAR or VAr in practice);

Complex power, $\boldsymbol{S}$ in volt-amperes (VA) or multiples thereof e.g. kVA;

Apparent power, $|\boldsymbol{S}|$ which is the magnitude of complex power and also in volt-amperes (VA);

Phase of voltage relative to current, φ which is the angle of difference (in degrees or radians) between current and voltage; the cosine of this phase angle is the Power Factor (PF) of the system. If the current phasor is lagging the voltage phasor then complex power is a quadrant I phasor; if the current phasor is leading the voltage phasor then the complex power is a quadrant IV phasor.

In a simple AC circuit consisting of a source and a linear time-invariant load, both the current and voltage are sinusoidal at the same frequency. If the load is purely resistive, the two quantities reverse their polarity at the same time. At every instant the product of voltage and current is positive or zero, the result being that the direction of energy flow does not reverse. In this case, only active power is transferred.

If the load is purely reactive, then the voltage and current are 90 degrees out of phase. For two quarters of each cycle, the product of voltage and current is positive, but for the other two quarters, the product is negative, indicating that on average, exactly as much energy flows into the load as flows back out. There is no net energy flow over each half cycle. In this case, only reactive power flows; there is no net transfer of energy to the load; however, electric power does flow along the wires and returns by flowing in reverse along the same wires. The current required for this reactive power flow dissipates energy on the line resistance, even if the ideal load device consumes no energy itself. Practical loads have resistance as well as inductance, or capacitance, so both active and reactive powers will flow to actual loads.

Apparent power is the product of the rms values of sinusoidal voltage and current. Apparent power is considered when designing and operating power systems, because although the current associated with reactive power does no work at the load, it still must be supplied by the power source. Conductors, transformers and generators must be sized to carry the total current, not just the current that does useful work. Failure to provide for the supply of sufficient reactive power in electrical grids can lead to lowered voltage levels and, under certain operating conditions, to the complete collapse of the network or blackout. Another consequence is that adding the apparent power for two loads will not accurately give the total power unless they have the same phase difference between current and voltage (the same power factor, see below).

Conventionally, capacitors are treated as if they generate reactive power, and inductors are treated as if they consume it. If a capacitor and an inductor are placed in parallel, then the currents flowing through the capacitor and the inductor tend to cancel rather than add. This is the fundamental mechanism for controlling the power factor in electric power transmission; capacitors (or inductors) are inserted in a circuit to partially compensate for reactive power 'consumed' ('generated') by the load. Purely capacitive circuits supply reactive power with the current waveform leading the voltage waveform by 90 degrees, while purely inductive circuits absorb reactive power with the current waveform lagging the voltage waveform by 90 degrees. The result of this is that capacitive and inductive circuit elements tend to cancel each other out.

A.3 Energy Forms in Microscopic Scales

Energy in microscopic scales is either associated with a fundamental interaction force of nature or arising as kinetic energy of particles (Dhanak & Xiros, 2016). When associated with a fundamental interaction is oftentimes manifested as a mass defect (or mass deficit) that a system (typically consisting of particles) exhibits when its mass is compared to the sum of the masses of the standalone components making it up (Blank et al., 1985). The best-known example is that of atomic nuclei where the mass of an atomic nucleus is slightly smaller than the sum of the masses of the individual nucleons (protons and neutrons) making up the nucleus. This mass deficit corresponds through Einstein's equation $E = mc^2$ to the binding energy developing between the nucleons thanks to the strong nuclear force. The force carrier particle of the strong interaction is the gluon which is massless.

Another, less known example is the binding energy of an atom. This is thanks to the electromagnetic interaction developing between the positive electric charge of the nucleus and the negative electric charge of electrons. If one adds the individual masses of the electrons and the nucleus a slight deficit will be observed with respect to the recorded mass of the atom as a whole. Photons are massless elementary particles serving as quanta of the electromagnetic field, including electromagnetic radiation such as light, radio waves etc. and the force carrier of the electromagnetic interaction.

In nuclear physics and particle physics, the weak interaction, which is also often called the weak force or weak nuclear force, is one of the four known fundamental interactions. It is the mechanism of interaction between subatomic particles that is responsible for the radioactive decay of atoms. The weak interaction participates in nuclear fission and nuclear fusion. The Standard Model of particle physics describes the electromagnetic interaction and the weak interaction as two different aspects of a single electroweak interaction. This theory was developed around 1968 by Sheldon Glashow, Abdus Salam, and Steven Weinberg, and they were awarded the 1979 Nobel Prize in Physics for their work.

Gravity is the weakest of the four fundamental interactions of physics, approximately 10^{38} times weaker than the strong interaction, 10^{36} times weaker than the electromagnetic force and 10^{29} times weaker than the weak interaction (Dhanak & Xiros, 2016). Consequently, it has no significant influence at the level of subatomic particles. In contrast, it is the dominant interaction at the macroscopic scale, and is the cause of the formation, shape and trajectory (orbit) of celestial bodies. Attempts to develop a theory of gravity consistent with quantum mechanics, a quantum gravity theory, which would allow gravity to be united in a common mathematical framework (a theory of everything) with the other three fundamental interactions of physics, are a current area of research. Gravity is most accurately described by the general theory of relativity proposed by Albert Einstein in 1915, which describes gravity not as a force, but as the curvature of spacetime, caused by the uneven distribution of mass, and causing masses to move along geodesic lines. The most extreme example of this curvature of spacetime is a black hole, from which nothing (not even light) can escape once past the black hole's event horizon. However, for most applications, gravity is well approximated by Newton's law of universal gravitation, which describes gravity as a force causing any two bodies to be attracted toward each other, with magnitude proportional to the product of their masses and inversely proportional to the square of the distance between them.

An account of the Newtonian kinetic energy was given in the previous section. In modern physics, kinetic energy is also understood as relativistic kinetic energy as well as an observable and an operator in quantum mechanics. In special relativity theory, the relativistic mass of an object is given by the relativistic energy divided by c^2 (speed of light squared). Because the relativistic mass is exactly proportional to the relativistic energy, relativistic mass and relativistic energy are nearly synonymous; the only difference between them is the units. The rest mass or invariant mass of an object is defined as the mass an object has in its rest frame, when it is not moving with respect to the observer. Physicists typically use the term mass, though experiments have shown an object's gravitational mass depends on its total energy and not just its rest mass. The rest mass is the same for all inertial frames, as it is independent of the motion of the observer, it is the smallest possible value of the relativistic mass of the object. Because of the attraction between components of a system, which results in potential energy, the rest mass is almost never additive; in general, the mass of an object is not the sum of the masses of its parts. The rest mass of an object is the total energy of all the parts, including kinetic energy, as observed from the center of momentum frame, and potential energy. The masses add up only if the constituents are at rest as observed from the center of momentum frame and do not attract or repel, so that they do not have any extra kinetic or potential energy. Massless particles like photons and gluons are particles with no rest mass and therefore have no intrinsic energy; their energy is due only to their momentum. Finally, in quantum mechanics, observables like kinetic energy are represented as operators. For one particle with known mass, the kinetic energy operator appears as a term in the Hamiltonian and is defined in terms of the more fundamental momentum operator.

A.4 Energy Forms Nomenclature

SYMBOL	*DEFINITION*
SI	International System of Units (Système International)
t, τ	Time, temporal variable or time interval
$\boldsymbol{x}, x$	Position or distance vector and scalar
W	Work
ϑ	Angle or arc in radians unless other unit specified
$\boldsymbol{r}$	Radius or lever arm length
$\boldsymbol{F}, F_{\vartheta}$	Force vector, force tangential component (scalar)
M	Torque (moment of force) magnitude (scalar) in newton-meters (SI)
E	Energy
m	Mass
$\boldsymbol{v}, v$	Velocity vector and scalar speed
$\boldsymbol{a}$	Acceleration vector
I	(Mass) moment of inertia (rotational inertia) in kilogram-meter-squared (SI)
ω	Angular or rotational velocity magnitude (scalar) in radians per second (SI)
z	Height or topographic altitude or bathymetric depth in gravity field
k	Constant of spring stiffness in newtons per meter (SI)
U	Internal energy
u	Specific internal energy in joules per kilogram (SI)
p	Pressure (absolute, not gauge, unless otherwise specified)
V	Volume
v	Specific volume in cubic meters per kilogram (SI)
ρ	(Mass) density in kilograms per cubic meter (SI)
T	Absolute temperature in kelvins (SI)
R	Specific gas constant in joules per kelvin and per kilogram (SI)
c_V	Specific heat capacity at constant volume in same units as R
c_p	Specific heat capacity at constant pressure in same units as R
H	Enthalpy in joules (SI)
h	Specific enthalpy in joules per kilogram (SI)
S	Entropy in joules per kelvin (SI)
$\Delta(\blacksquare)$	Difference or change of a variable, final minus initial value
$d(\blacksquare)$	Exact differential e.g. enthalpy or entropy in thermodynamics
$\delta(\blacksquare)$	Imperfect (or inexact) differential e.g. work or heat in thermodynamics

Q	Heat in joules (SI)
$\dot{Q}$	Heat (transfer) flow rate in joules per second (i.e. watts in SI)
$\dot{W}$	Mechanical power, work produced or consumed per unit time in watts (SI)
$\dot{m}$	Mass flow rate in kilograms per second (SI)
$\dot{V}$	Volumetric flow rate in cubic meters per second (SI)
q	Electric charge in coulombs (SI)
dc (or DC)	Direct current
ac (or AC)	Alternating current
U	Electrostatic potential in joules per coulomb (i.e. volts in SI)
$\mathbf{E}$	Electric field in volts per meter (SI)
$\mathbf{B}$	Magnetic induction in newtons per ampere and per meter (i.e. tesla in SI)
i	Electric current (amperage) in coulombs per second (i.e. amperes in SI)
v	Voltage in volts (SI)
p	Instantaneous electric power in watts (SI)
R	Resistance of electric resistor in ohms (SI)
G	Conductance of electric resistor or conductor in siemens (mhos) in SI
$\partial(\blacksquare)$	Boundary defining an enclosed surface or enclosed volume
A	Capacitor’s plate or inductor’s core cross-section area in square meters (SI)
$d\mathbf{A}$	Vector of surface area differential
ℓ	Distance between capacitor plates or length of inductor’s core in meters (SI)
$d\boldsymbol{\ell}$	Vector of inductor’s core differential length
$\Sigma\mathrm{q}$	Total electric charge incl. free and bound enclosed in volume
C	Capacitance of capacitor in coulombs per volt i.e. farads (F) in SI
S	Surface
ε_0	Vacuum or air permittivity approx. 8.85×10^{-12} F/m (farads per meter)
Σi	Total electric current incl. free and bound enclosed in surface
N	Number of turns in an inductor’s solenoid
Φ	Magnetic flux (scalar) in weber (SI)
L	Inductance of inductor in weber per ampere i.e. henrys (H) in SI
μ_0	Vacuum or air permeability approx. $4\pi \times 10^{-7}$ H/m (henrys per meter)
j	Square root of negative one, $\mathrm{j} = \sqrt{-1}$
rms	Also encountered as RMS, Root-Mean-Square value
V	RMS value of sinusoidal ac voltage waveform
I	RMS value of sinusoidal ac current waveform

$\boldsymbol{V}$	AC voltage phasor, i.e. vector on the complex plane
$\boldsymbol{I}$	AC current phasor, i.e. vector on the complex plane
$(\blacksquare)^*$	Complex conjugate applied e.g. on current phasor or complex power
$\boldsymbol{S}$	Complex power (vector) in volt-amperes (VA)
$\lvert\boldsymbol{S}\rvert$	Apparent power (nonnegative real scalar) in volt-amperes (VA)
P	Active (i.e. real) power in watts (W)
Q	Reactive power in volt-ampere-reactive (var or VAR or VAr)
φ or φ	Angle (i.e. argument) difference between current and voltage phasors
PF	Power Factor also encountered as cosφ

B Imprint

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