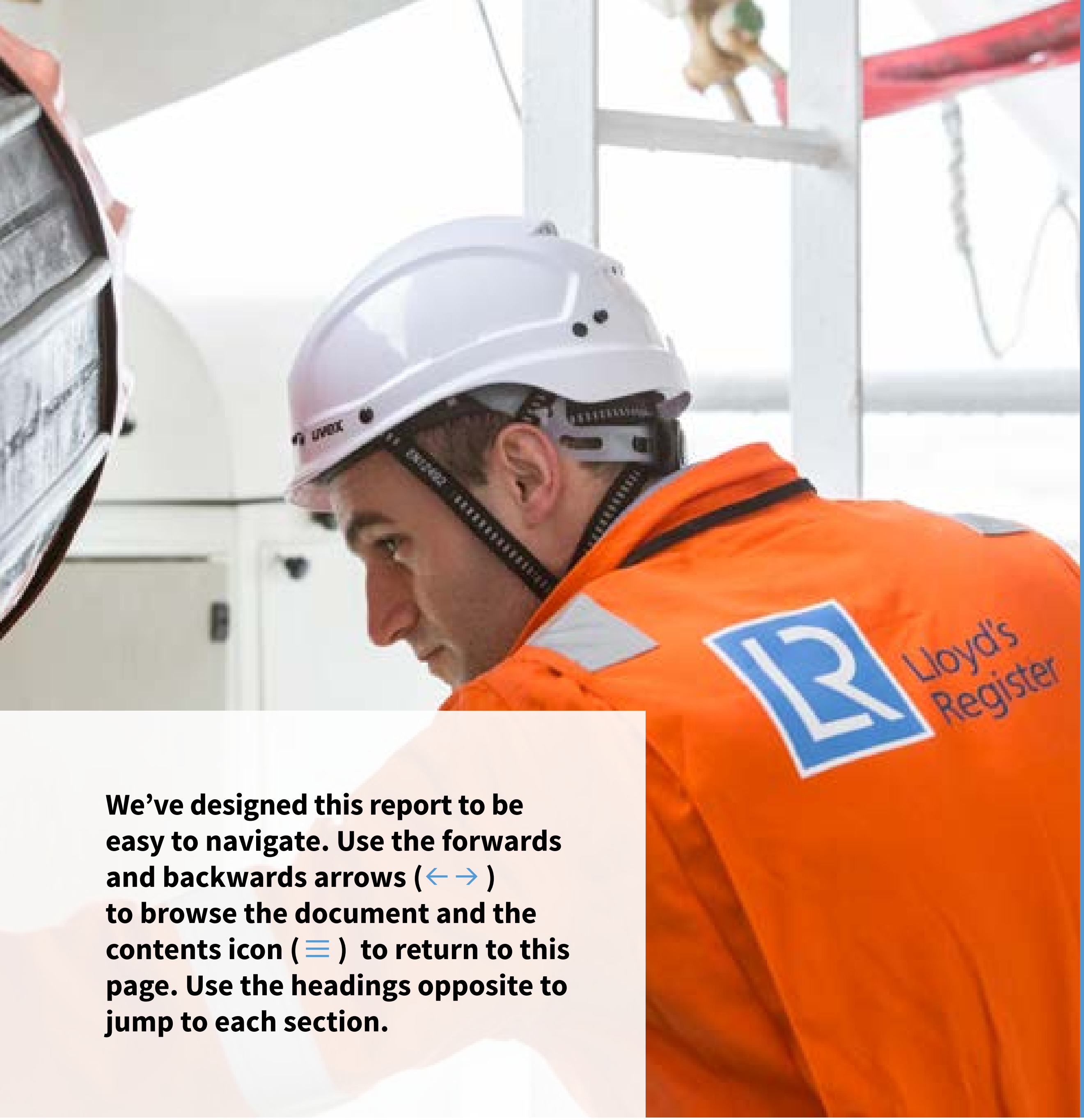
# Safety considerations for the use of zero-carbon fuels and technologies.

*This is part of Zero-Emission Vessels:*
*Transition Pathways*

Lloyd's Register

UMAS



**We’ve designed this report to be easy to navigate. Use the forwards and backwards arrows ( ← → ) to browse the document and the contents icon ( ≡ ) to return to this page. Use the headings opposite to jump to each section.**

# Contents

# Safety considerations for the use of zero-carbon fuels and technologies.

Achieving the level of ambition set out in the initial International Maritime Organization (IMO) greenhouse gas (GHG) strategy will require zero-emission vessels to enter the fleet in 2030 and from then on will form a significant proportion of newbuilds. Different solutions have different benefits for different types of ships. It is important that zero-carbon solutions are not only viable from a commercial perspective, but also technically feasible and can be safely adopted and operated.

Compared to fossil fuels, around which the shipping industry has had decades to optimize the design, maintenance and operation of the shipping system, the introduction of zero-carbon fuels and associated technologies brings with it new safety risks that need to be mitigated or managed. This is due to the properties of these fuels and also because they are less energy dense fuels, requiring ships using them to hold greater quantities onboard.

Hydrogen, for example, when stored as a liquid, needs to be kept at temperatures just above absolute zero. If cryogenic liquids such as these are accidentally released, they could crack unprotected steel, expand to hundreds of times their original volume and become flammable as they turn back to gas. This would be a serious problem if it occurred below deck, where ships generally store their fuel. Hydrogen is also far easier to ignite than fossil fuels, while if methanol ignites, its flames are almost impossible to detect without specialist equipment. All zero-carbon fuel options produce a flame that emits light outside the visible range, therefore prevention, ventilation and detection principles need to apply.

The current risk management landscape is designed to meet the demands of known fuels such as heavy fuel oil (HFO), marine diesel oil (MDO) and liquefied natural gas (LNG). The properties that characterise zero-carbon fuel options and the need for larger quantities mean that the safety risks presented to crew, passengers and others can be very different to those posed by fossil fuels. For example, buoyancy is an important characteristic of these fuels. Although the safety philosophy of prevention, detection and ventilation still applies, such fuel properties may require a radical change in routine ship design regarding such aspects as the position of venting and gas detection.

Safety standards will be achieved through rigorous hazard studies. To ensure safety, different and more sophisticated equipment and safeguards are needed. These require greater knowledge and skill to design, manufacture, inspect, install, commission, survey, operate and maintain.

Safety assessments inform the design to ensure that equipment works efficiently and that appropriate safeguards are in place. This would mean that no matter what the fuel system is, the chance of an accident is minimised and the consequences limited.

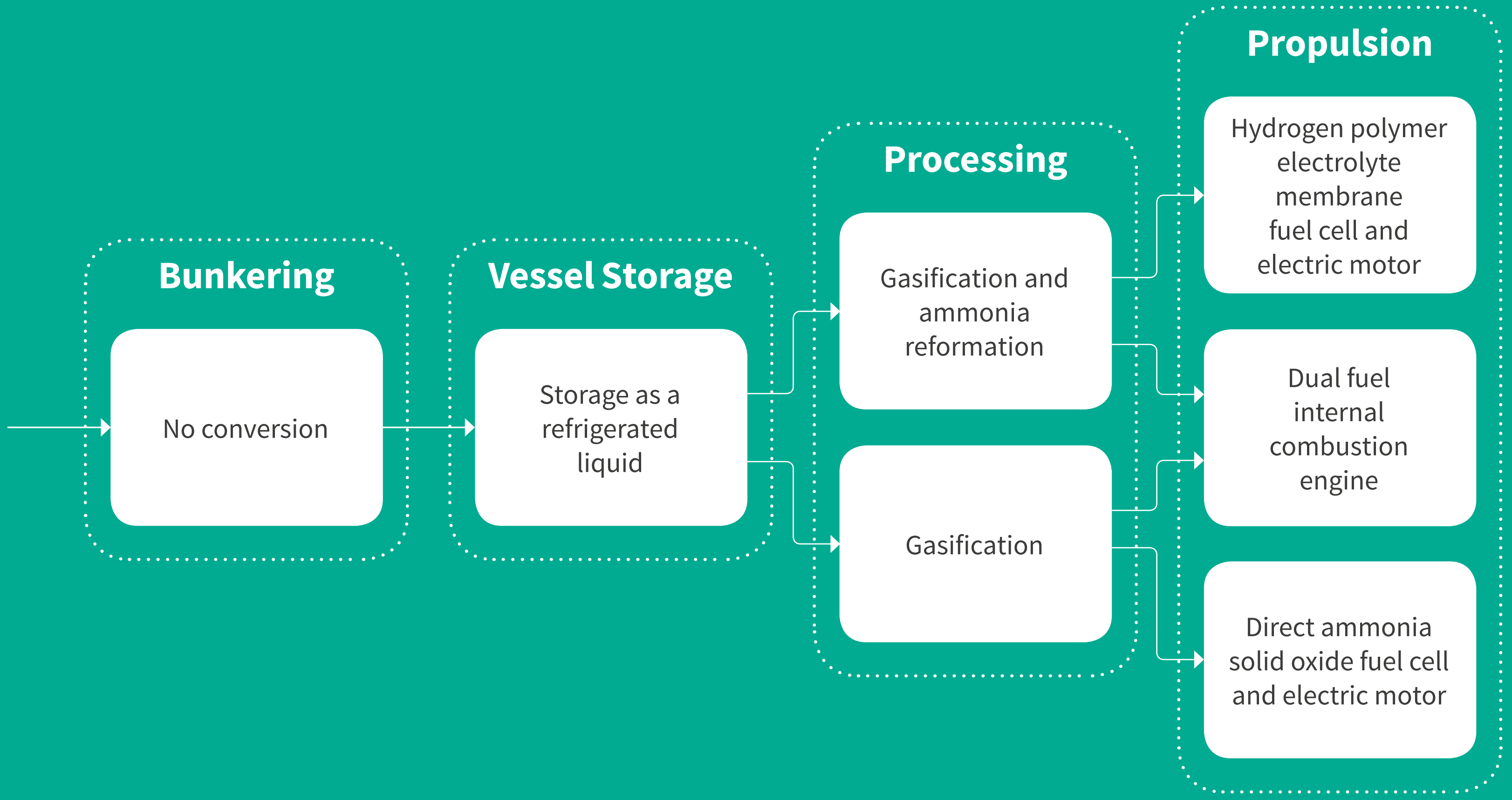
There is no doubt that the shipping industry needs to decarbonise, but we should not underestimate the hazards and risks that zero- carbon fuels and technologies present. So we need to ensure that safety standards are maintained or enhanced where possible.

AMMONIA

# Fuel characteristics.

- Ammonia ($NH_3$) is a colourless, flammable, highly toxic and corrosive gas with a suffocating odour that requires appropriate management
- It is highly soluble in water and commonly sold in liquid form, so it evaporates quickly
- Ammonia has a similar energy content to methanol and hydrogen
- Ammonia has a low flammability (15-28%), but measures need to be taken to control ignition sources
- Avoid contact and inhalation as exposure can result in burns and asphyxiation
- It has a very strong odour (smell detection threshold between 0.04-20 parts per million (ppm)), which is much lower than dangerous levels (above 1000 ppm exposure is likely required for 10-30 minutes for a fatal dose, immediately dangerous to life or health (IDLH) is 300 ppm). This means that small releases that do not cause injury can result in discomfort
- Ammonia has a slow flame speed, which means when used in internal combustion engines it generally requires another combustion medium

## AMMONIA
(CONTINUED)



**Bunkering**

No conversion

**Vessel Storage**

Storage as a refrigerated liquid

**Processing**

Gasification and ammonia reformation

Gasification

**Propulsion**

Hydrogen polymer electrolyte membrane fuel cell and electric motor

Dual fuel internal combustion engine

Direct ammonia solid oxide fuel cell and electric motor

Bunking | Vessel Storage | Processing | **Propulsion**

Low pressure release (cold ammonia) with pool spill and evaporation will give buoyant gas behaviour, i.e. shorter safety distances outdoor (bunkering) and accumulation/detection near ceiling (confined rooms). Higher pressure releases (warm ammonia) will give flashing ammonia sprays with dense gas behaviour in which ammonia stays near ground. This can give higher safety distances outdoor.

Bunking | Vessel Storage | Processing | **Propulsion**

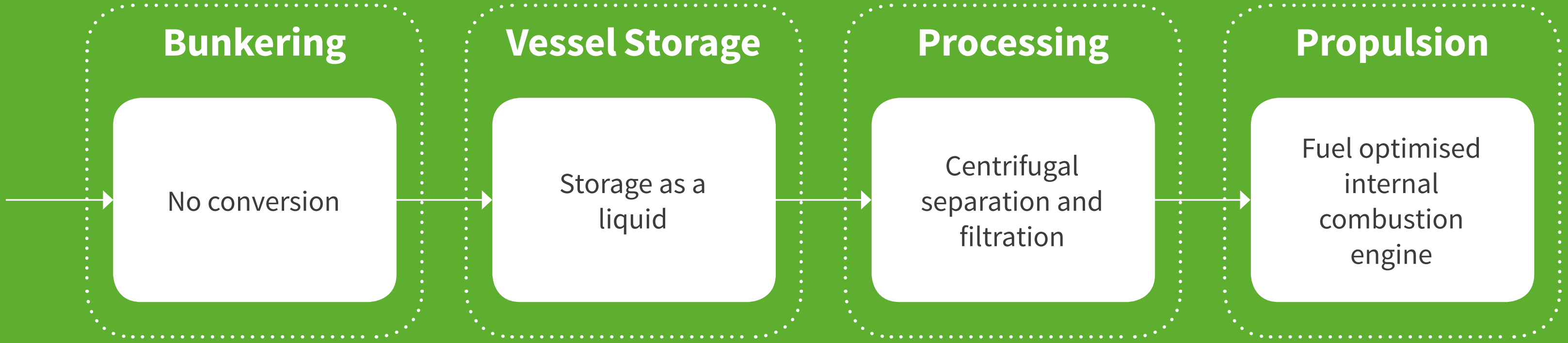
Release and leakage in internal combustion engines resulting in fires and explosions.

Click each element for more information.

# Fuel characteristics.

- Biofuels are produced directly or indirectly from organic material and categorised based on the source
    - First generation: produced directly from food crops or producing bioethanol through fermentation. Crops such as wheat and sugar are used as feedstock for bioethanol and oil seed rape for use in biodiesel
    - Second generation: they are produced from non-food crops such as wood, organic waste, food crop waste and specific biomass crops
    - Third generation: specially engineered energy crops such as algae as its energy and source
- Functionally they are equivalent to petroleum-derived fuels and compatible with existing infrastructure and machinery
- Biodiesels such as fatty acid methyl ester (FAME) can function as a drop-in but it has a lower boiling point and viscosity and higher flashpoint compared to a petroleum-derived diesel, which means it degrades quickly in water and has a high cloud point, which can result in filter clogging and poor fuel flow at low temperatures
- Alternatively, Straight Vegetable Oils (SVOs) have a high viscosity and boiling point, which can reduce the engine lifespan due to carbon deposit build-up. These types of biofuels would need to be pre-heated prior to engine injection or used as a blend
- Biodiesels have a lower energy output when compared with petroleum-derived diesels. Biodiesel energy density is typically 38 megajoule/kilogram (MJ/Kg) compared to 46 MJ/Kg for diesel
- Technical compatibility of biofuels with marine engines appears high and integration manageable

## BIOFUELS
(CONTINUED)



**Bunkering**

No conversion

**Vessel Storage**

Storage as a liquid

**Processing**

Centrifugal separation and filtration

**Propulsion**

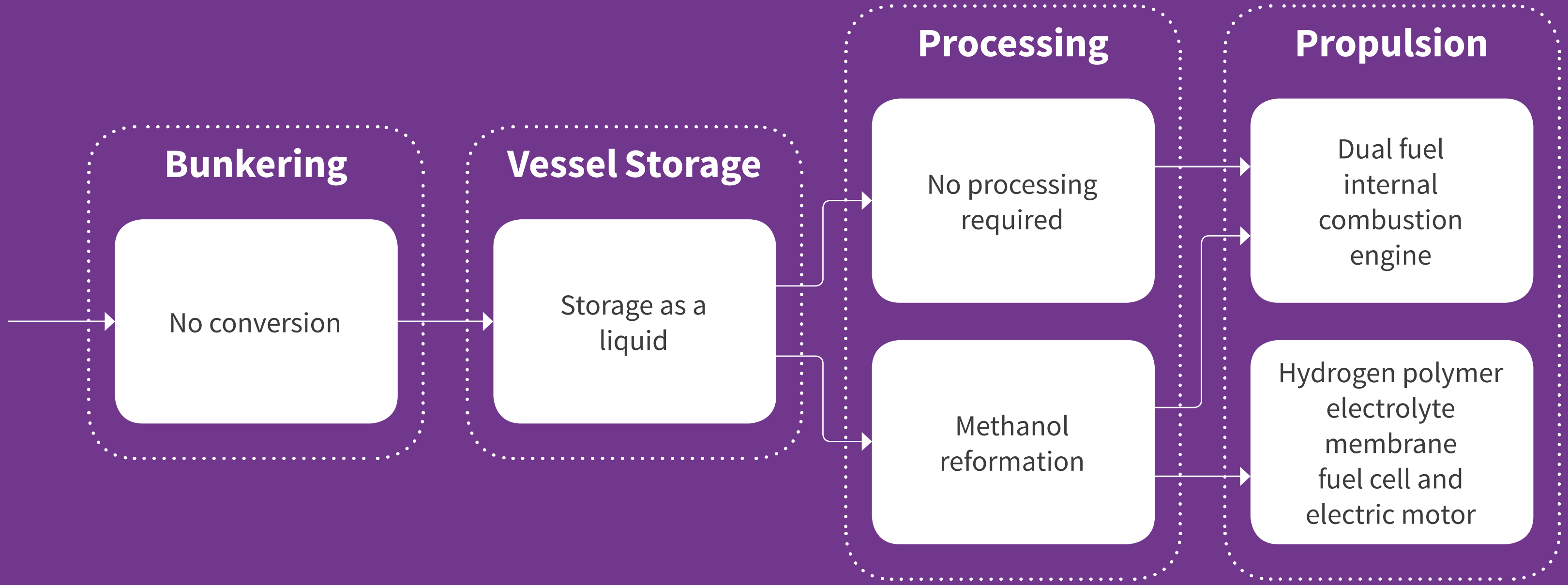
Fuel optimised internal combustion engine

Click each element for more information.

# Fuel characteristics.

- Methanol is a liquid between 176-338 Kelvin (-98°C to +65°C) at atmospheric pressure
- It is a neutrally buoyant fuel which is highly toxic with an invisible flame
- It has a lower density and heating value compared to petroleum-derived fuels and is considered a low flashpoint fuel (11°C – 12°C)
- Water solubility makes it impossible to remove water that may have entered the fuel stream during bunkering, affecting energy density and combustion quality
- It is highly toxic to human health
- Fire, explosion and human contact during transmission are the key risks
- It is not readily visible or detected without specialist equipment

METHANOL
(CONTINUED)



Click each element for more information.

# Fuel characteristics.

- Given its molecular properties, hydrogen is typically stored at high pressures (up to 700 bar-g) or extremely low temperatures (-253°C at ambient pressure) to achieve the necessary energy density
- Compared with other flammable gases, it has a wider flammability limit, low ignition energy and high flame velocity with an invisible flame during combustion
- Its high flame velocity can result in detonation in confined spaces
- Given its minimal molecular size, hydrogen is very permeable, diffusing through containment materials
- Gaseous hydrogen is highly buoyant, whereas ammonia cannot become neutrally buoyant in certain conditions (humidity etc.), and methanol is neutrally buoyant

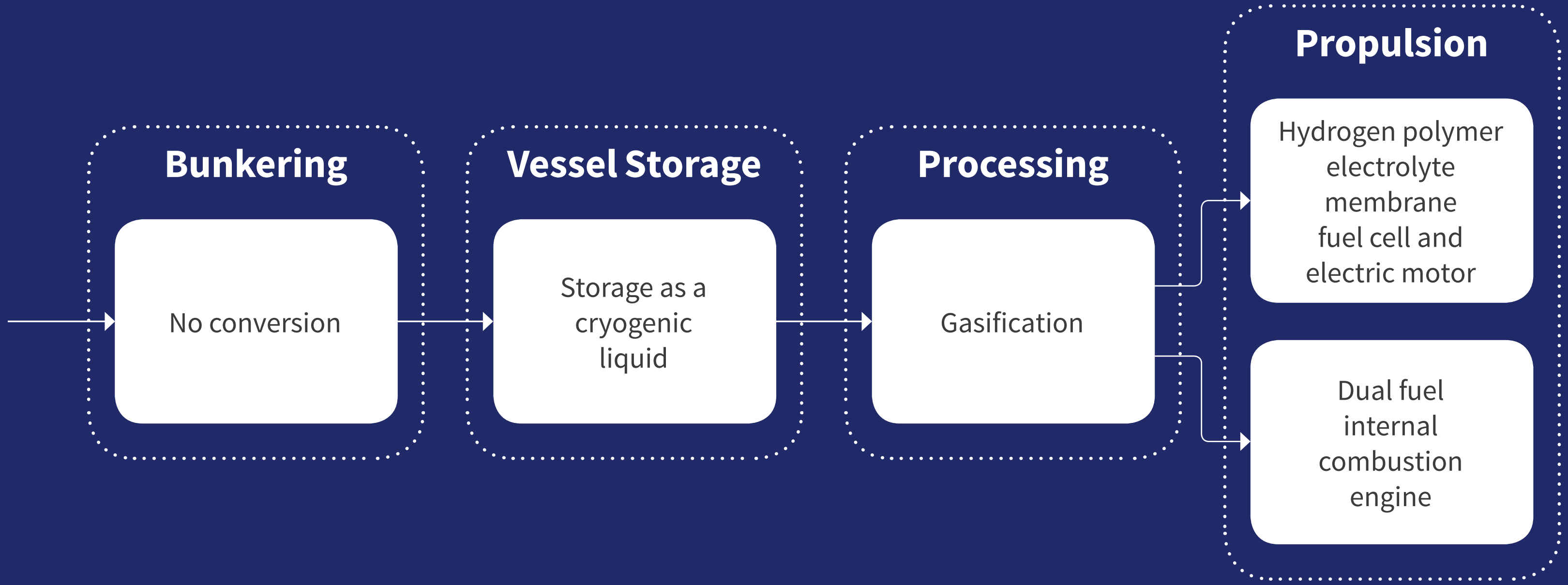
## Compressed Hydrogen

- Rupture of high pressure hydrogen tanks releases a large amount of energy (not necessarily because of hydrogen but as a result of the containment pressures involved)
- High pressure releases (leakage, venting) can result in auto-ignition (spontaneous ignition)
- Ignition of high pressure releases will result in jet fires

## Liquefied Hydrogen

- Liquefied hydrogen leakage (-253°C) can be catastrophic for unprotected steel structures (immediate loss of toughness and embrittlement of carbon steel)
- With large, unmitigated liquid hydrogen releases, hydrogen vapours can remain heavier than air for prolonged periods
- Within the immediate vicinity of release, liquid hydrogen can liquefy/freeze air, resulting in $O_2$ doping increasing its reactivity with hydrogen vapours

# HYDROGEN
(CONTINUED)



**Bunkering**

No conversion

**Vessel Storage**

Storage as a cryogenic liquid

**Processing**

Gasification

**Propulsion**

Hydrogen polymer electrolyte membrane fuel cell and electric motor

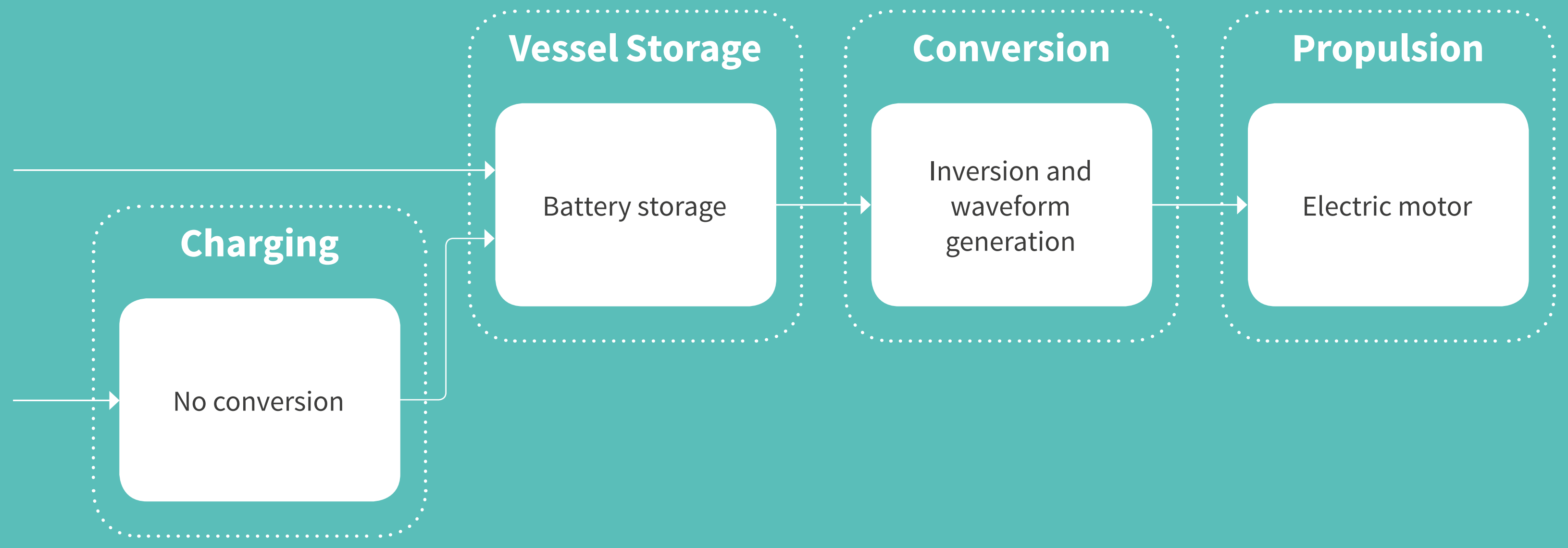
Dual fuel internal combustion engine

Click each element for more information.

# Technology characteristics.

- There is a wide variation of battery chemistries, design and construction. Even with Lithium-Ion types, there are a number of distinct chemistries, architectures and manufacturing employed, requiring specific regulations and testing requirements to mitigate against specific failure modes
- Performance and health degradation at adverse temperature operations
- Thermal runaway remains a prominent failure mode, originating from crushing, damage, overcharging, over-depletion, shorting fault events
- Battery failure consequences include venting of toxic, flammable gas, fire and explosion
- Monitoring capability: currently sensing involves temperature and voltage monitoring at the module/ battery level. Yet most degradations, anomalies and faults originate at the cellular level (cell – module – battery – power system)

BATTERIES
(CONTINUED)



Click each element for more information.

# Technology characteristics.

- Fuel cells undergo a chemical process to convert chemical-based fuels into electricity, such as hydrogen, ammonia and methanol
- Fuel cells are very clean, with their only by-products being electricity, excess heat and water. In addition, as fuel cells do not have any moving parts, they operate near-silently
- The lifespan of a fuel cell is highly dependent on the quality of the fuel used
- The main hazards with fuel cells result from uncontrolled reactions, loss of containment of fuels and side reactions

# Maintaining safety.

To enable the transition to zero-carbon fuels, we need to ensure that an equivalent level of safety or greater is achieved. A zero-emission vessel will depend on the integration of a number of novel and/or complex technologies.

## Continued adoption of goal-based requirements

The International Code of Safety for Ships using Gases or other low-flashpoint fuels (IGF Code) is the mandatory IMO instrument code. Although regulations for methanol and low flashpoint diesel fuels, as well as for fuel cells, are under development, standards and lessons learned from the deployment of these zero-carbon fuels in other industry sectors can be applied.

The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) would also apply for boil-off gas, such as ammonia and potentially liquid hydrogen in the future.

Taking a risk-based approach to design, operation and maintenance LR rules cover;

- Rules such as Hybrid Power Systems, Li-ion batteries, Safety Critical Software, alternative fuels such as methanol and hydrogen
- The rigorous application of Risk Based Design process and Approval In Principle enables a step by step approach to safety inserting new technology into the system
- Progression towards virtual assurance techniques, such as Digital Compliance

Safety philosophies need to be tailored to the fuel. Operating ships with new fuels and maintaining new technologies will require new competencies and skill sets and therefore competence and capability will be key to enable this transition.

Key areas of focus are:

- Autonomous systems (shipping) reduce the risks by virtue of reducing exposure
- Design to be considered with the usability of systems and equipment
- Designing equipment and allocating responsibilities according to the mental capabilities and limitations of users
- The organisational integrity of the operation as a whole

## Use of digital applications to improve efficiency

Zero-emission vessels will require new analysis and appraisal capabilities to address integration, cyber-enablement, new technologies such as batteries, alternative fuel storage and an all-electric ship.

These fuels and technologies enable opportunities for a less disruptive and more efficient business model by using data gathered to enhance performance and confirm safe implementation, operation and maintenance.

**info.lr.org**

**www.u-mas.co.uk**

**info.lr.org/ZEV-transition-pathways**

**January 2019**