



**EUROMOT**

The European Association of Internal  
Combustion Engine and Alternative  
Powertrain Manufacturers

# The Role of Powertrains in Decarbonising Society

EUROMOT Guiding Principles to Decarbonise  
Non-Road Mobile Machinery, Rail, Marine  
and Power Plant Applications

**Full Report**

March 2026

# The Role of Powertrains in Decarbonising Society

EUROMOT Guiding Principles to Decarbonise Non-Road  
Mobile Machinery, Rail, Marine and Power Plant Applications

This document is one of a portfolio of decarbonisation  
reports produced by EUROMOT, which are:

1. EUROMOT Guiding Principles
2. Executive Summary
3. Full Report
4. Sector-specific Summary Reports:
  - Non-road Mobile Machinery
  - Forestry, Lawn and Utility
  - Marine Inland Waterway Transport
  - Seagoing Marine
  - Marine Recreational Craft
  - Rail
  - Stationary

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# Introduction

*In this paper we use the term 'decarbonisation' to describe the process of reducing the greenhouse gas emissions associated with an activity, towards a sustainable, net zero level.*

EUROMOT has established a set of guiding principles to accelerate decarbonisation in non-road mobile machinery, marine, rail and stationary applications<sup>1</sup>.

## Those core principles are:

### Technology neutrality:

- Facilitate a diversified energy mix and do not be tempted to force a single technology.
- Base overall GHG reduction objectives in each industry sector on Life Cycle Analysis (LCA) considering different end uses and do not focus solely on emissions at point of use.

### Predictable global approach:

- Align activities and levels of ambition at international level recognising internal combustion engines, alternative powertrains and the applications in which they are installed are developed for global markets.

### Recognition of the needs of end users:

- Ensure the continued ability to deliver dependable power to perform the intended task wherever it is needed.
- Ensure the availability of new low or net zero greenhouse gas (GHG) energy carriers at competitive costs.
- Facilitate the availability and use of low and net zero GHG energy carriers suitable for existing in-use products.

*Life Cycle Analysis (LCA) is a method of calculating the total CO<sub>2</sub>e emissions from a product, including other emissions such as nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>), during its full lifecycle. That is throughout manufacture, use and disposal.*

*Well to Wheel, (or Well to Wake for marine) (WtW), emissions is the total (net) emissions generated when a fuel or energy carrier is created (such as when it is extracted from the ground or grown as a biological feedstock), when its energy has been converted in a machine and its end products emitted (e.g. CO<sub>2</sub> and water from burning a hydrocarbon fuel).*

This paper expands upon those core principles. It highlights examples of the needs of end users and identifies viable and practical powertrains that could be used to reduce the carbon intensity<sup>2</sup> of their work tasks.

Whilst this paper focuses on the required attributes of the powertrains, the selection of the powertrain is only part of the overall equation. The powertrain must not be considered in isolation from the resources needed to create and eventually dispose of the machines or power plants and the efficacy, efficiency and productivity with which they will perform the intended task.

Finally, it is notable that end users across the industries served by EUROMOT members generally need to compete for business, so the cost of new technologies compared to incumbent powertrains will be a key factor influencing adoption.

<sup>1</sup>EUROMOT (2023) The role of internal combustion engines and alternative powertrains in decarbonisation

<sup>2</sup>We use the term carbon intensity as defined in the Renewable Energy Directive (RED), as amended. European Union (2018) Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the European Union, L 328, pp. 82-209.



# About EUROMOT

EUROMOT, the European Association of Internal Combustion Engine and Alternative Powertrain Manufacturers, represents the key manufacturers of internal combustion engines and alternative powertrains installed in Construction, Agriculture and Industrial; Forestry, Lawn and Utility; Marine; Rail; and Stationary power plant applications that are operating in Europe and globally.

Founded in 1991, we provide a recognised hub of expertise for businesses, authorities, regulators, and public stakeholders worldwide. In partnership with major sector associations and institutions, it is our mission to advocate better regulation, and to foster innovation that supports our sustainability and industry objectives.

Delivering reliable power for society at high energy conversion efficiency with low emissions remains a key objective of EUROMOT member companies. EUROMOT asserts internal combustion engines and alternative powertrains are a key enabler to address decarbonisation across multiple industry sectors. This can be achieved by continuing to advance the development of flexible highly efficient energy conversion systems capable of operating on various low and net zero greenhouse gas emissions energy carriers.

# Our Members



# Background

## How new powertrain technologies and fuels can help decarbonise the industrial and consumer activities they power

Powertrains for non-road mobile machinery (NRMM), marine, rail and power plants drive some of the world's major mechanised industries and maintain the continuity of critical services. The continued evolution of the powertrains for these working machines will make a significant contribution to decarbonising European and global industrial sectors.

*Yet, there is no simple or single solution to decarbonise the powertrains of this diverse array of machines with equally diverse functions, patterns of use, and operating environments.*

EUROMOT examines how the attributes of a range of powertrain technologies and alternative energy carriers fit with the needs of the end users. It identifies a range of potential decarbonisation pathways suited to the example applications, use cases and operating environments.

*With a particular focus on initiatives including the EU Green Deal, Fit for 55, the IMO GHG Reduction Strategy, the Competitiveness Compass, the Draghi Report, and the Clean Industrial Deal, this paper concludes that successful decarbonisation must harness the full toolkit of new technologies and energy carriers and focus on reducing GHG emissions across entire lifecycles. Additionally, integrating climate-neutral policies with industrial, competition, economic, and trade policies, as emphasised in the Competitiveness Compass and Draghi Report, will be crucial in driving growth and reducing dependencies on fossil fuels.<sup>3</sup>*

The decarbonisation pathways for this diverse range of use cases require an equally diverse mix of solutions.

## The powertrain industry's view on its contribution to decarbonising society

This paper represents the powertrain industry's view on the viable and practical choice of pathways to deliver sustainable and reliable power across Europe and the world. These powertrains drive many and diverse applications from the harvesters producing food, power station generators balancing the grid, excavators mining raw materials and building infrastructure, chainsaws for selective timber harvesting or clean-up work after a storm, ships and trains moving goods by land and sea, and the armoured vehicles and vessels at the heart of defence. They also provide backup power for data centres, the emergency power that maintains critical services from hospitals to fire brigades and provide flexibility to renewable grids.

The EU Green Deal and Fit for 55, along with similar initiatives elsewhere, require major emissions reductions across a broad range of sectors from buildings to energy.<sup>4</sup>

*Reducing the GHG emissions from industrial powertrains will also enable decarbonisation of the wider supply chains and sectors they support.*

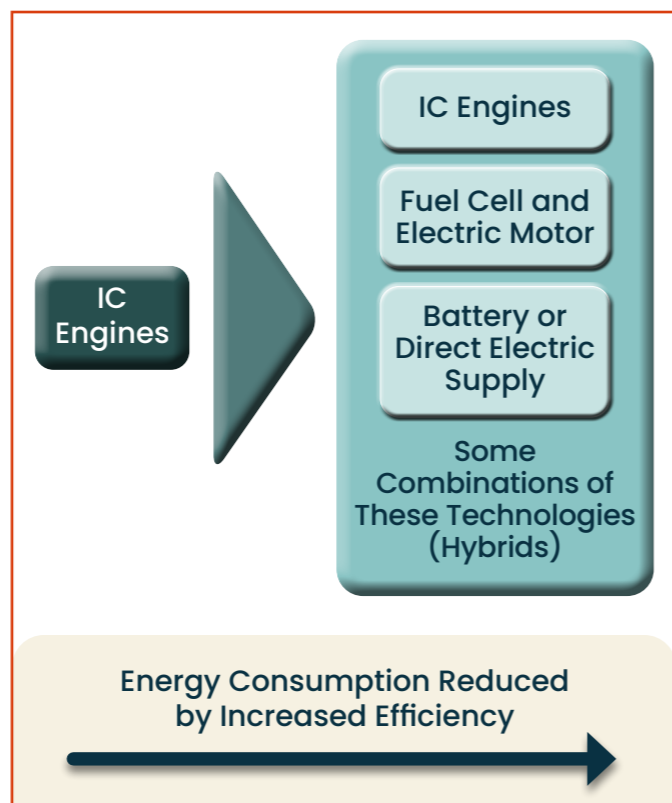
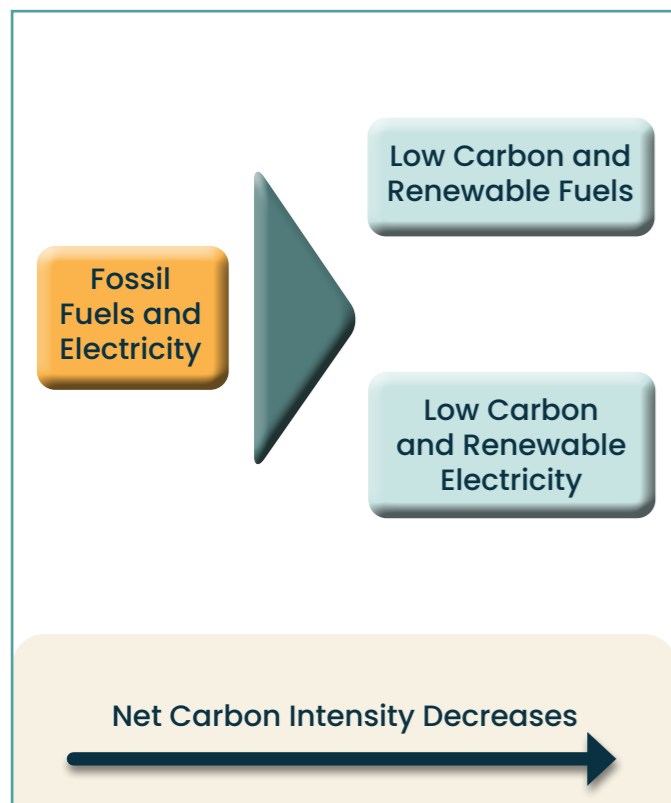
Industrial powertrains also drive the machinery behind end-to-end processes, from raw material mining to waste handling, so that new powertrains could reduce carbon emissions across end-to-end product lifecycles.

<sup>4</sup>EUROMOT (2023) The role of internal combustion engines and alternative powertrains in decarbonisation

<sup>3</sup>This paper reflects the regulatory environment of mid 2025.

### Energy Carriers

### Energy Converters



### CO<sub>2</sub> Emissions Decrease



A successful evolution towards low and zero GHG emissions powertrains will involve many intermediate steps. This is essential to reduce GHG emissions across existing powertrain applications while ensuring new technologies and energy carriers can fulfil these diverse industrial demands.

**An orderly transition involves adopting energy efficiency improvements and the use of low carbon and renewable fuels.**

Industry is already making major progress through energy efficiency improvements to powertrains and the way they are applied in different machines, the progressive switch towards more carbon-efficient patterns of operation, and growing adoption of low carbon and renewable fuels. EUROMOT members are also already fully engaged in developing and launching new powertrain technologies to accelerate progress towards net zero GHG emissions.

While the powertrains outlined within this paper offer pathways to decarbonisation, we need to progressively reduce GHG emissions from the manufacturing, use and disposal phase of the powertrain's life.

This paper represents the powertrain industry's view on the choice of routes to deliver sustainable and reliable power across Europe and the world.



# Key factors to consider for decarbonising Non-Road Mobile Machinery, Rail, Marine and Power Plant Applications

*Decarbonisation solutions for this industry must accommodate a diverse array of applications, operating environments, energy needs, and patterns of use.*

These range from handheld tools such as hedge trimmers to high-powered applications such as tunnel boring

machines and from large oceangoing vessels like tankers to stationary applications including power plants.

They operate in environments ranging from seas and cities to rural regions, running both intermittently and continuously, alone or in combination, and with applications as diverse as construction and defence.

## Range of use cases, operational demands, and environments to consider

Output of powertrain units ranges from < 1 kW up to 100 MW

Running times can vary from short periods to long, including running continuously for up to weeks at a time



The largest powertrains can consume up to several GWh of energy a day

Fuel/energy is nearly always delivered to the machines or power plants, especially those used in remote areas. For hand-held equipment used on remote sites both the machine and energy source have to be carried by hand throughout the work task



Operating environments range from urban to remote locations such as islands, oceans and forests

Power plants need fast startups and shutdowns to sustain emergency services or support grid flexibility

The availability of a range of powertrain capabilities using diverse energy carriers ensures strategic independence in times of fuel supply shortages or the need for disaster relief

For hand-held equipment a low machine weight and ergonomic design, including the energy storage unit, is crucial for safe and efficacious operation



Alternative powertrains must be of a size and weight that enables industrial machines and power plants to perform the tasks for which they are intended.

Decarbonisation pathways must also consider the many cases where electrification is not viable such as remote, energy-intensive applications with round-the-clock operations.

### Evaluation of these low emissions technologies also needs to factor in other key criteria including:

Facilitate adoption to ensure widespread use.

Availability of secure supply chains and material sources such as precious and rare-earth metals, and the technical feasibility and technological maturity of the powertrains

Cost-competitiveness to drive maximum market penetration and ensure mechanised industry products remain internationally competitive

Availability of the required energy carrier production, distribution, and storage networks across all operating environments

## Additional considerations

### Speed of deployment of low and net zero carbon technologies

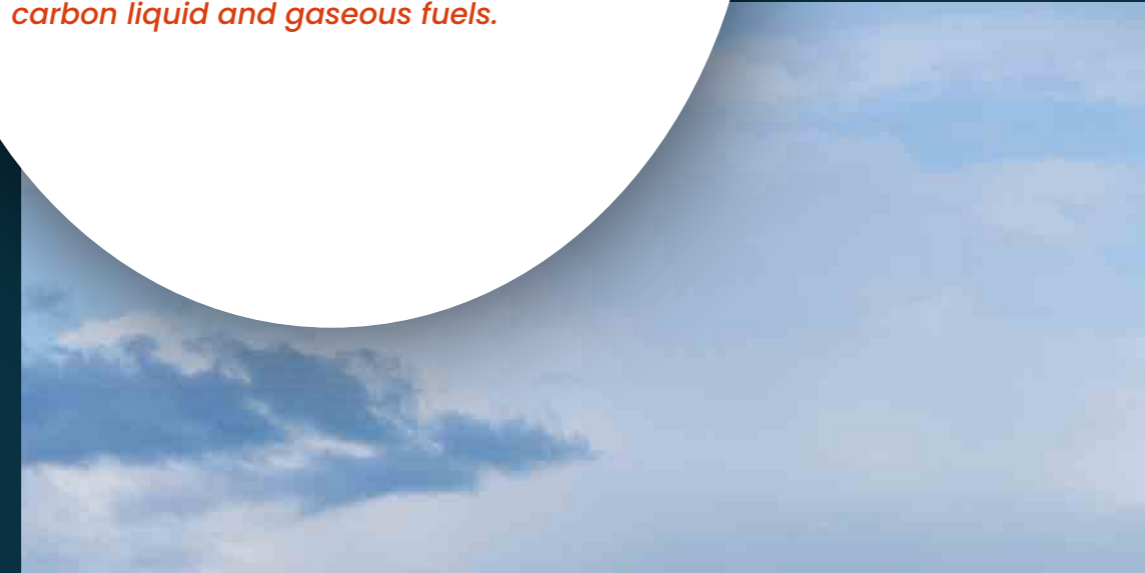
- Many machines and power plants have long lives in several phases of ownership. Decarbonisation strategies must consider this to ensure early and progressive decarbonisation.
- Drop-in reduced carbon, low carbon and renewable fuels used in the existing fleet of machines and power plants offer an important opportunity to reduce GHG emissions ahead of machine or plant replacement.
- Efficiency improvements and use of reduced, low and net-zero carbon energy carriers are important to achieve progress on decarbonisation in the short, medium and long term.



*Achieving the desired GHG emissions reductions across such a diverse range of use cases will require a technology neutral, all-encompassing approach including a diverse array of solutions catering to a wide variety of industrial demands.*

*A smooth, orderly transition to new powertrains and energy carriers must be grounded in real-world expertise from all the relevant sectors. For these reasons, any standards or policies must be technology neutral, allowing industry to develop the technical solutions to enable the widest possible adoption.*

*Policy should focus on provision of all the required production and distribution networks for energy carriers, specifically renewable electricity, hydrogen and its derivatives, ammonia, low and net zero carbon liquid and gaseous fuels.*



# Powertrain technologies offering pathways to decarbonisation

This section compares the key attributes, strengths, and weaknesses of all known industrial powertrain technologies. This will be key to assessing the viability of each technology and fuel for their many different industrial applications, operating environments and demands. We also look at the range of energy carriers these technologies can use to reduce GHG emissions. These technologies may also be combined in various hybrid configurations, where appropriate to the use of machines and plants.

Internal Combustion Engines (ICEs) using hydrocarbon fuels are the historic, and incumbent powertrain technology for almost all applications in these sectors. ICEs have been developed over many decades to give efficiently delivered, reliable and dependable power at an affordable cost. ICEs can continue to have these attributes whilst offering a pathway to decarbonisation by using reduced carbon, low carbon, non carbon and renewable fuels.

The powertrain technologies, that are available to support decarbonisation, and their attributes, are shown here.

## Internal combustion engines

<p><b>Efficiency</b></p> <p>Highly operationally efficient as the most compact powertrain technology with readily available, energy-dense fuel sources and fast refuelling times.</p> <p><b>Up to 55% energy conversion efficiency.</b></p>	<p><b>Emissions</b></p> <p>Potential for decarbonisation when using reduced carbon, low carbon, and renewable fuels (including non carbon fuels such as hydrogen and ammonia). Lower embedded GHG emissions* than fuel cells or electric powertrain technologies.</p>	<p><b>Technological maturity</b></p> <p>Proven technology across all industrial applications and use cases.</p> <p><b>Security, cost, and availability</b></p> <p>Secure, domestic supply chains and readily available material sources except some precious materials used in aftertreatment.</p>
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## Hydrogen fuel cells with batteries and electric motors

<p><b>Efficiency</b></p> <p>Similar refuelling times to ICEs but hydrogen tanks need 4-8x onboard storage space of diesel tanks. Can achieve up to 60% energy conversion efficiency for some applications (efficiencies may reduce with use).</p>	<p><b>Emissions</b></p> <p>Zero air quality or GHG emissions at point of use. Medium embedded GHG emissions*.</p>	<p><b>Technological maturity</b></p> <p>Technology already in use in on-road applications including cars and forklift trucks, but unproven in non-road industrial sectors such as construction.</p> <p><b>Security, cost, and availability</b></p> <p>Supply chain costs and risks around some components. Fuel cell systems for dynamic applications require a hybrid configuration with batteries.</p>
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## Electric Motors – Continuous electric supply or with battery storage

<p><b>Efficiency</b></p> <p>The highest energy conversion efficiency technology giving <b>75-90% efficiency</b>.</p> <p>The overall operational efficiency can be reduced by downtime due to charging, and the extra storage space needed for large onboard batteries.</p>	<p><b>Emissions</b></p> <p>Zero GHG emissions at the point of use. Higher embedded GHG emissions* than ICEs.</p>	<p><b>Technological maturity</b></p> <p>Proven technology across some industrial applications.</p> <p><b>Security, cost, and availability</b></p> <p>Supply chain security risks, high costs and projected shortages for raw materials and components in batteries and motors.</p>
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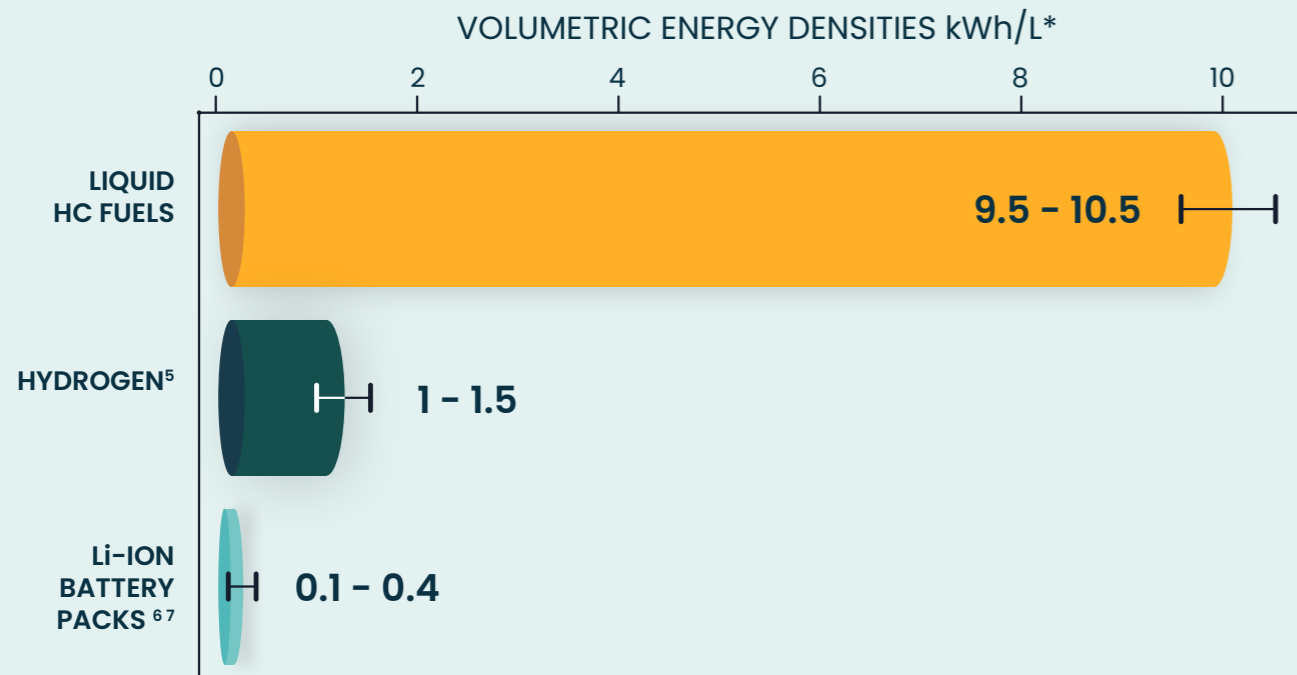
\*"Embedded GHG emissions" refer to the greenhouse gas emissions associated with the production, transportation, and disposal of a product or material, but not necessarily emitted during its use.

# Energy carriers offering pathways to net zero

There is a wide array of alternative fuels capable of replacing fossil diesel and gasoline and providing pathways to decarbonisation for all powertrains. These range from low carbon fuels that could significantly reduce emissions across the existing machine fleet in the short term to renewable fuels that could fully decarbonise future powertrains over

the longer term. These alternative fuels will be essential to decarbonise the many powertrain sectors, applications, and use cases where battery electric is not technically viable or practical, from sectors such as marine and applications such as power generation to use cases such as heavy machinery in remote locations.

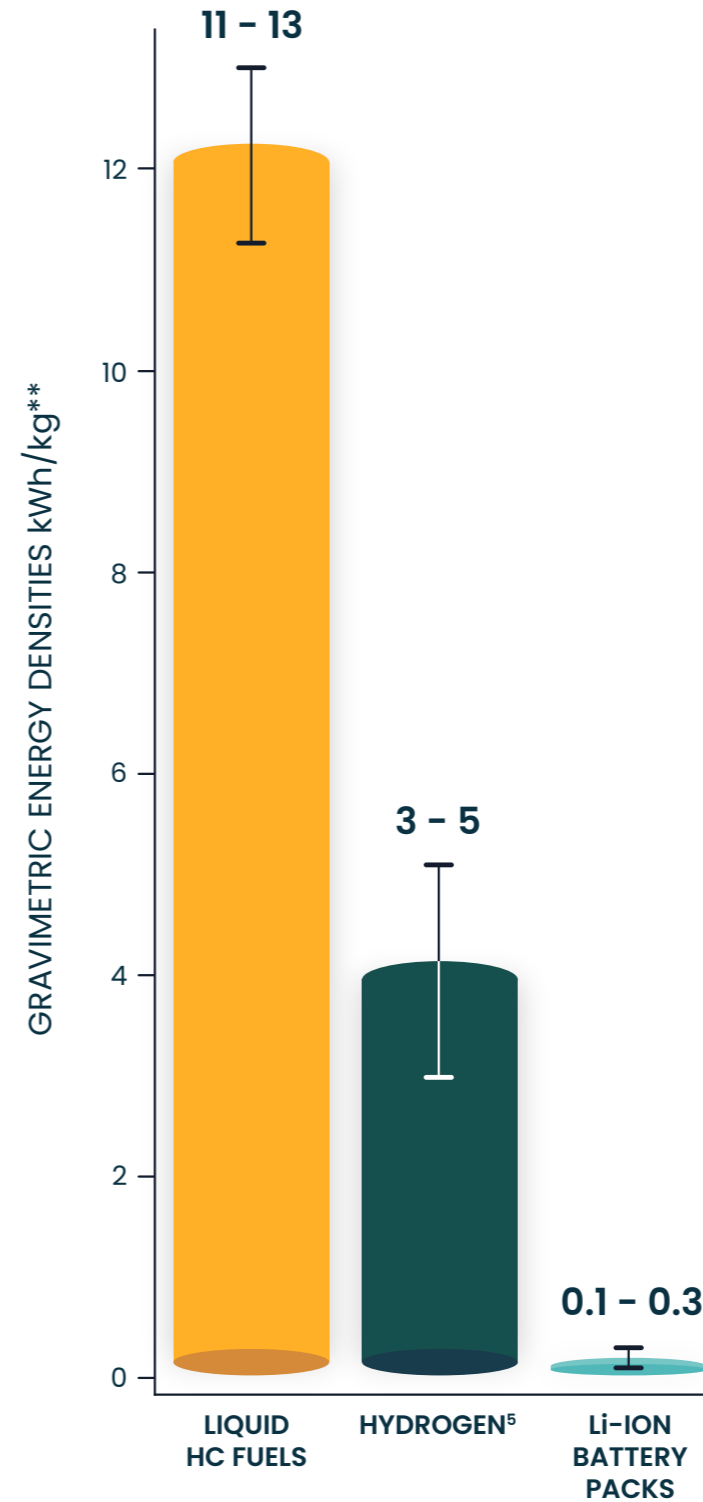
## Comparing energy densities for compressed hydrogen, liquid hydrocarbon (HC) fuels and lithium-ion (Li-ion) batteries



<sup>5</sup>Compressed to 700 bar including the tank.

<sup>6</sup>STIHL. (2023). AP 300 S Battery.

<sup>7</sup>Husqvarna. (2025). Akku B330X.



\*Energy carriers with lower volumetric energy density need more onboard storage space, affecting their use in applications where space is at a premium

\*\*Energy carriers with lower gravimetric energy density are heavier, which affects their feasibility for applications where weight is at a premium

There are different understandings of the names given to fuel types. We are using the following definitions

### Fossil fuels

Derived from ancient organic matter, fossil fuels like coal, oil, and natural gas are burned for energy. Their combustion releases greenhouse gases, contributing to global warming. Unlike renewable fuels, fossil fuels are finite and environmentally impactful

### Reduced carbon fuels

Fuels where the CF is lower than the fossil fuels they replace, for example natural gas replacing diesel/fuel oil; B20 biodiesel; E50 gasoline

### Low carbon fuels

Fuels where the CF is >70% lower than their fossil equivalent

### Renewable fuels

Fuels of biological or non-biological origin where the stored energy comes from renewable sources; either solar energy via photosynthesis or from renewable electricity. The EU Renewable Energy Directives (REDs) require the Carbon Footprint (CF) of renewable fuels to be >70% lower than their fossil equivalent

### Non carbon fuels

Fuels that do not contain carbon such as hydrogen and ammonia (not necessarily renewable)

## Reduced carbon, low carbon and renewable fuels tables

### Liquid Fossil Fuels

### Gasoline, Diesel, Fuel Oil

#### Fuel Category

Fossil.

#### Decarbonisation Potential

Baseline.

#### Energy Density and Ease of Adoption

High energy density. Incumbent fuels.

#### Drop-in Potential

Baseline.

#### Handling Requirements

Handling processes established. Baseline.

#### Air Quality Emissions

Baseline.



In this paper we refer to CO<sub>2</sub> equivalent emissions, taking into account emissions of other GHGs. Methane, Nitrous oxide and Hydrogen have a significant GHG potential

and methane slip or hydrogen slip and production of nitrous oxides from engines are carefully controlled.

### Gaseous Fossil Fuels

### Natural Gas, LPG

#### Fuel Category

Reduced carbon.

#### Decarbonisation Potential

10% - 20% lower tailpipe CO<sub>2</sub> than diesel or gasoline.

#### Energy Density and Ease of Adoption

High energy density. Similar storage space and refuelling as incumbent fuels.

#### Drop-in Potential

Not a drop-in for diesel or gasoline, but engines can be modified to use them.

#### Handling Requirements

Stored under pressure or as liquids.

#### Air Quality Emissions

Similar to, or lower than diesel. Can be controlled to very low levels with latest technology.

### Gaseous Biofuels

### Biogas, Biomethane

#### Fuel Category

Renewable.

#### Decarbonisation Potential

High level of decarbonisation possible when made with renewable feedstocks and methods.

#### Energy Density and Ease of Adoption

High energy density. Same refuelling requirements as natural gas.

#### Drop-in Potential

Drop-in replacement for natural gas.

#### Handling Requirements

Same handling requirements as natural gas.

#### Air Quality Emissions

Similar to, or lower than diesel. Can be controlled to very low levels with latest technology.

**Liquid Biofuels & Biomass fuels** | **HVO, Biogasoline, Biodiesel, Ethanol**

**Fuel Category**

Renewable, or reduced carbon if blended with fossil fuels.

**Decarbonisation Potential**

High level of decarbonisation possible when made with renewable feedstocks and methods. When blended, decarbonisation is dependent on the proportions of the blend.

**Energy Density and Ease of Adoption**

High energy density. Similar handling and fill times as liquid fossil fuels.

**Drop-in Potential**

HVO can be used as a drop-in fuel. Others can be drop-in when blended with fossil fuels. Minor engine modifications to use pure biofuels.

**Handling Requirements**

Same as liquid fossil fuels.

**Air Quality Emissions**

Similar to fossil equivalent. Can be controlled to very low levels with latest technology.

**Non Carbon Fuels** | **Hydrogen, Ammonia**

**Fuel Category**

Renewable if made using renewable electricity. Low carbon if made using non renewable electricity or from natural gas with carbon capture.

**Decarbonisation Potential**

Zero tailpipe CO<sub>2</sub>. Can approach net zero when produced using renewable electricity.

**Energy Density and Ease of Adoption**

Medium energy density when stored as liquids or as high pressure gas.

**Drop-in Potential**

Not drop-in fuels. Can be used in dedicated ICEs. Hydrogen can be used in fuel cells. Some ICEs can be modified to use ammonia.

**Handling Requirements**

**Hydrogen:** high pressure or very cold liquid. Protection from contamination or ignition.

**Ammonia:** Stored as liquid or high pressure gas. Corrosive and toxic.

**Air Quality Emissions**

Fuel cells do not emit AQ emissions at point of use. There are no carbon derived air quality emissions from the ammonia or hydrogen combustion. NO<sub>x</sub> emissions can be controlled to very low levels.

**E-Fuels** | **e-Gasoline, e-Diesel, e-Methanol, e-Methane**

**Fuel Category**

Renewable if made using renewable electricity and captured or biogenic CO<sub>2</sub>. Low Carbon if non renewable electricity used.

**Decarbonisation Potential**

Can approach net zero when using renewable electricity and captured or biogenic CO<sub>2</sub>. High levels of decarbonisation are still possible when using higher carbon intensity electricity.

**Energy Density and Ease of Adoption**

High energy density. Similar handling and fill times as liquid fossil fuels.

**Drop-in Potential**

Drop-in fuels for the fossil equivalent in ICEs.

**Handling Requirements**

Same as liquid fossil fuels.

**Air Quality Emissions**

Similar to fossil fuel equivalent. Can be controlled to very low levels with latest technology.

**Electricity** | **Grid, Generator, Battery Storage**

**Fuel Category**

Renewable if generated from renewable energy. Low carbon if generated from low carbon energy e.g. nuclear. Reduced carbon from e.g. natural gas. Fossil from e.g. coal.

**Decarbonisation Potential**

Approaches net zero when renewable energy sources are used.

**Energy Density and Ease of Adoption**

Electricity has to be used as it is generated, or stored in for example batteries. When stored in batteries it has low energy density. There are challenges to adoption as machines have to be continuously connected to a power source, or use batteries which have low energy density.

**Drop-in Potential**

Not a drop-in for ICE powered applications.

**Handling Requirements**

Using electricity over 60 V, special measures may be needed.

**Air Quality Emissions**

No AQ emissions in use. The generation process may emit pollutants.

# General Conclusion

Powertrains are at the heart of the many diverse machines and power plants that society relies on. From the harvesters producing food; generators balancing the grid; excavators mining raw materials and building infrastructure; chainsaws for timber harvesting and forest maintenance; ships and trains moving goods by land and sea.

The machines and power plants used in these various sectors vary widely in size, power output and energy consumption. There is a massive range of uses with some applications running a few hours a year to others running continuously for extended periods. Many powertrain applications are used in remote or undeveloped locations with constrained infrastructure. Energy is nearly always supplied to the machines or power plants at their work site or location. Successful decarbonisation of these different sectors, applications and uses thus requires the full range of power conversion technologies and energy carriers.

## Recommendations

Manufacturers are developing powertrains and power plants that support decarbonisation of all the sectors in which they are used. For successful deployment of these technologies, policy and regulation need to be technology neutral, recognising the need for the full array of decarbonisation pathways, and assessing them on a life cycle basis (LCA method).

Policy also needs to enable supply and distribution of renewable electricity and low carbon and renewable fuels. This includes production of drop-in low carbon and net zero fuels for use in existing equipment. This will be critical to balance decarbonisation with the continuing need for dependable power across society.

EUROMOT has developed a set of principles that guide the industry's decarbonisation pathway, whilst supporting the needs of end users. These are:

### Technology neutrality:

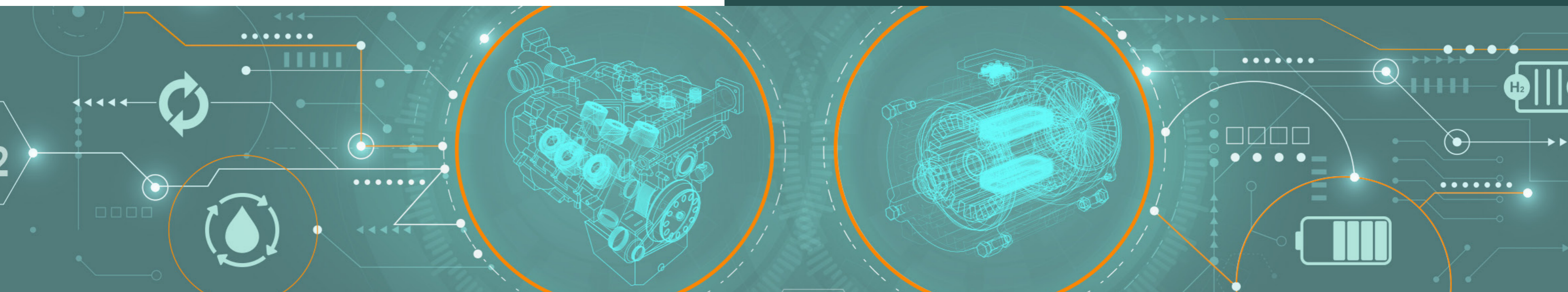
- Facilitate a diversified energy mix and do not be tempted to force a single technology.
- Base overall GHG reduction objectives in each industry sector on Life Cycle Analysis (LCA), considering different end uses and do not focus solely on emissions at point of use.

### Predictable global approach:

- Aligning activities and levels of ambition at international level recognising internal combustion engines, alternative powertrains and the applications in which they are installed are developed for global markets.

### Recognition of the needs of end users:

- Ensuring the continued ability to deliver dependable power to perform the intended task wherever it is needed.
- Ensure the availability of new low or net zero greenhouse gas (GHG) energy carriers at competitive costs.
- Facilitating the availability and use of low and net zero GHG energy carriers suitable for existing in-use products.





02

# Non-Road Mobile Machinery (NRMM)

The sector encompasses a wide array of industrial machines that either move under their own power or can be moved between sites with vital economic applications including agricultural, construction and material handling machines, mobile generator sets and transportable industrial plants. Their power ranges from 1 kW to over 2,500 kW, patterns of use extend from light and intermittent to heavy-duty 24-hour operations in environments from urban to remote locations where fuel or energy must be taken to the machine. Even one type of machine can be used for vastly different purposes from agriculture to construction. Ownership patterns vary from individual owner-operators and small farms through to large plant hire and agricultural contracting companies.

Small businesses would not be able to own multiple machines with different powertrain types and may have to become selective in the work they undertake. Larger businesses may purchase a variety of machines with different powertrains, though the range of use cases into which a given machine could be deployed may be restricted.

The following sector examples span the main sub-sectors of NRMM, specifically Agriculture, Construction, Mobile Power Generation, Industrial and Other Sectors. They cover a broad sweep of applications and uses, demonstrating that decarbonisation solutions will need to be varied enough to support a wide range of industrial requirements and operating conditions.

These examples are not exhaustive, and do not represent the only pathways to decarbonisation for each type of machine. Each of these machines may require different powertrain technologies offering pathways to decarbonisation for different use cases.

The energy consumption numbers in the following examples include the efficiency of the ICE, i.e. they are comparable to the output of the electric motor of electric machines.



## Evaluation Criteria\*

## Use Case Evaluation

Energy use	Low	Is a large amount of energy used for the example task?	High
Work intensity	Low	Is the average power the machine is working at a high percentage of its maximum output power?	High
Type of use	Sporadic	Is the machine running for a high proportion of the task duration, or for a small portion?	Continuous
Availability of electricity on site	Available	Is electricity at a usable voltage and power available at the site of use of the machine?	Not available
Predictability of deployment	Pre-planned	Can the task be planned well in advance, or is it required to act urgently depending on circumstances?	Un-planned
Location of site	Adjacent to infrastructure	Is the machine being used in an area with infrastructure and service availability or any area without these?	Remote from infrastructure
Time on site	Extended	Is the time a machine is on site short i.e. days or weeks, or long i.e. months or years?	Short
Required machine mobility	Low	Does the machine used for the task move around the site (>100 m) or does it stay in one position?	High
Minimise refuelling/recharging	Infrequent	Is it important to complete task without significant downtime for refuelling/recharging	Fast

\*Terms used to explain the use case evaluations found in the following examples.

# Agriculture

## Example 1: Front-line field tractor

### Use description:

Used for ploughing, harrowing and planting on large arable farmland of over 100 hectares. The machine operates in remote rural environments at high intensities for periods exceeding 20 hours with usage dictated by the weather and crop cycles.

### Machine employed:

Agricultural tractor with **200 kW** engine running on diesel. Fuel consumption is typically up to **500 L** diesel per day (equivalent to a battery capacity of **2 MWh**).

### Decarbonisation pathways:

High density energy carriers are required that offer rapid refuelling and can be taken to the machine in the field. ICEs running on low carbon fuels, moving to renewable, gaseous and liquid fuels such as biomethane, synthetic diesel or renewable hydrogen. Fuels of biological origin may be favoured in the agricultural industry.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="85"/>	High
Work intensity	Low	<input type="range" value="85"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="85"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="15"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="85"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="85"/>	Short
Required machine mobility	Low	<input type="range" value="85"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="85"/>	Fast

## Example 2: Combine harvester

### Use description:

Harvesting crops continuously for up to 24 hours/day at high (75%) intensity in suitable weather when crops are ready for harvest. It is used for a few days at each farm in turn, across remote rural locations. Fuel is taken to the machine, and fast refuelling occurs in the field. Outside of harvest season, the machine is parked out of use until the next year.

### Machine employed:

Combine harvester with **400 kW** diesel engine. Fuel consumption is typically **1,800 L** of diesel a day (equivalent to a battery capacity of **7 MWh**).

### Decarbonisation pathways:

High density energy carriers are required that offer rapid refuelling and can be taken to the machine in the field. ICEs running on low carbon fuels, moving to renewable, liquid fuels. Fuels of biological origin may be favoured in the agricultural industry.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="85"/>	High
Work intensity	Low	<input type="range" value="85"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="85"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="15"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="85"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="85"/>	Short
Required machine mobility	Low	<input type="range" value="85"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="85"/>	Fast

### Example 3: General purpose tractor

**Use description:**

Used for towing, silage and support field work in a mix of medium sized farms of around 30-100 hectares including centralised livestock, dairy and dispersed arable farms. It has a load factor of 20-70% and is used at varying intensities including high intensity.

**Machine employed:**

130 kW tractor. Fuel consumption is typically 100 L diesel a day (equivalent to battery capacity of 400 kWh).

**Decarbonisation pathways:**

ICEs running on low carbon liquid and gaseous fuels, moving to renewable fuels. Fuels of biological origin that could be produced on the farm may be favoured, such as biomethane (produced from manure). Other gaseous fuels such as hydrogen, may be feasible when available onsite, while battery electric is potentially viable for low intensity uses if onsite recharging infrastructure is available.



**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of use	Sporadic	<input type="range" value="75"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="25"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="75"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="75"/>	Short
Required machine mobility	Low	<input type="range" value="25"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="75"/>	Fast

## Example 4: Yard tractor

### Use description:

Small tractor used on various types of farms primarily for moving materials in barns, cleaning animal pens and other miscellaneous tasks. A range of intensities and load factors are experienced.

### Machine employed:

35–50 kW tractor. It runs on diesel. Fuel consumption is typically 25 L diesel per day (or equivalent to battery capacity of 100 kWh).

### Decarbonisation pathways:

ICEs running on low carbon liquid and gaseous fuels, moving to renewable fuels. Fuels of biological origin, that could be produced on the farm, may be favoured. Battery electric is feasible. The choice of powertrain will depend on the use case and which alternative energy carriers are available on farms.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="70"/>	High
Work intensity	Low	<input type="range" value="70"/>	High
Type of use	Sporadic	<input type="range" value="50"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="50"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="20"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="30"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="40"/>	Short
Required machine mobility	Low	<input type="range" value="20"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="30"/>	Fast

# Construction

## Example 1: Excavator for emergency reconstruction

### Use description:

Emergency rebuilding of remote breakwater after storm damage, operating continuously at high intensity for 20 hours a day for 10 days to finish its job before the arrival of spring tides. It is refuelled once per day from a fuel tanker.

### Machine employed:

**20 tonne** excavator with a **125 kW** diesel engine. Fuel consumption is typically **300 L** per day (or equivalent to battery capacity of **1,250 kWh**).

### Decarbonisation pathways:

Diesel could be replaced with low carbon liquid fuels moving to liquid renewable fuels. Whilst battery electric 20 tonne excavators are viable, they have limited battery capacity and are not suited to extended or continuous operation or for emergency use in areas where a suitable electricity supply is not available. It could run on hydrogen, but this would require refuelling 3-5 times a day.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="80"/>	High
Work intensity	Low	<input type="range" value="80"/>	High
Type of use	Sporadic	<input type="range" value="80"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="20"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="20"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="50"/>	Short
Required machine mobility	Low	<input type="range" value="80"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="20"/>	Fast

## Example 2: Excavator for housing construction

### Use description:

Part of a fleet of 10 similar sized excavators, dump trucks and loading shovels, used for groundworks in new housing developments. It operates continuously for 16-hour shifts at moderate intensity.

### Machine employed:

**20 tonne** excavator with **125 kW** diesel engine. Fuel consumption is typically **200 L** per day (or equivalent to battery capacity of **800 kWh**).

### Decarbonisation pathways:

Low carbon liquid or gaseous fuels moving to renewable fuels such as biofuels, synthetic diesel or renewable hydrogen. It is currently refuelled once a day but would need to be refuelled 2-3 times a day with hydrogen. Electrification is unlikely to be practical as the necessary infrastructure is not currently available onsite, and electric power would require the installation of a high power supply and chargers, or battery packs brought to the site.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of use	Sporadic	<input type="range" value="75"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="25"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="75"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="75"/>	Short
Required machine mobility	Low	<input type="range" value="75"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="75"/>	Fast

### Example 3: Excavator for city centre basement redevelopment

**Use description:**

Excavating basements and moving materials in city centres, operating at low intensity for 10 hours a day.

**Machine employed:**

20 tonne excavator with 125 kW diesel engine. Fuel consumption is typically 80 L of diesel per day (or equivalent to battery capacity of 250 kWh).

**Decarbonisation pathways:**

Battery electric (or possibly direct electric) is a feasible and practical pathway as electricity is available onsite and there is time for battery charging. Alternatively, Internal Combustion Engine (ICE) machines using renewable fuels.



**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="50"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="50"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="10"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="10"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="50"/>	Short
Required machine mobility	Low	<input type="range" value="50"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="50"/>	Fast

## Example 4: Heavy machines in a large quarry

### Use description:

Extraction and processing of large quantities of rock. Excavators and loading shovels load rocks into dump trucks that move the rock around site for further processing. Loading shovels load rock into tipper trucks for transport off site. The quarry site is in use for a decade or longer.

### Machines employed:

Large excavators (> 50 tonne) at the quarry face; smaller excavators for processing (30–50 tonne); dump trucks (30–60 tonne); loading shovels (> 5 m<sup>3</sup>).

### Decarbonisation pathways:

If electricity is available from the grid or onsite microgrids, direct electric or battery electric machines could be a viable option. ICE powered machines using renewable fuel could be used where microgrids are not available.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="85"/>	High
Work intensity	Low	<input type="range" value="85"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="15"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="15"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="15"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="15"/>	Short
Required machine mobility	Low	<input type="range" value="50"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="50"/>	Fast

# Industrial and Other Sectors

## Example 1: Large dump truck for open cast mining

### Use description:

Carrying mined ore from the lower level to the upper edge of open cast mines for processing. High intensity when going up fully laden, and low intensity when descending empty.

### Machine employed:

**100 tonne** dump truck powered by an ICE or ICE electric powertrain of **600 kW**. The combined energy from fuel and battery is used on the way up and energy recovered to the battery during descent.

### Decarbonisation pathways:

ICEs running on low carbon fuels, moving to renewable, liquid or gaseous fuels. A battery and energy recovery system can be added to the ICE electric powertrain to improve efficiency and reduce emissions. If there is high power, electrical infrastructure or a microgrid onsite, this can be used to supplement energy recovery to batteries, minimising fuel use for plug-in hybrids.

Alternatively, a pure battery electric powertrain could be used if there is time for charging or a system for charging on the move. With an average vehicle lifespan of over 30 years, low carbon and net zero drop-in fuels will be important to decarbonise the existing machine fleet. New powertrains will also need to be as durable as current machines.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="80"/>	High
Work intensity	Low	<input type="range" value="80"/>	High
Type of use	Sporadic	<input type="range" value="80"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="50"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="10"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="50"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="10"/>	Short
Required machine mobility	Low	<input type="range" value="80"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="50"/>	Fast

## Example 2: Telescopic handler for industrial, construction and farm operations

### Use description:

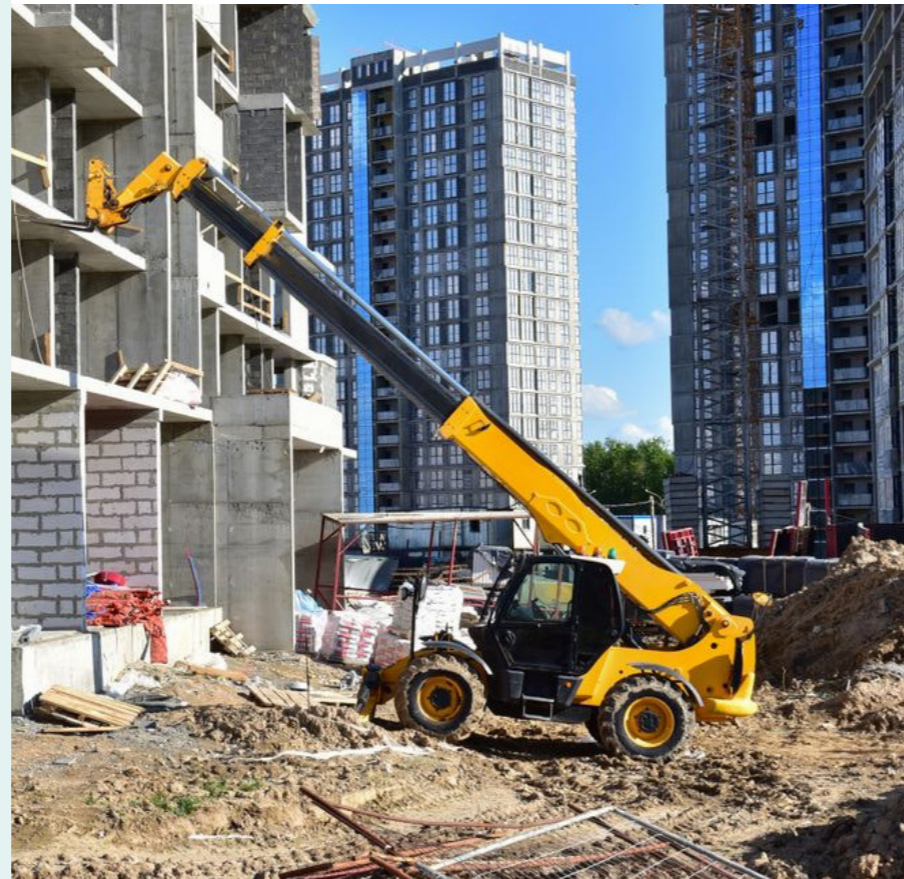
Moving materials around construction sites, industrial sites and farms. It has many use cases and operates anywhere from 1 to 20 hours a day at intensities ranging from 10–80%.

### Machine employed:

Telescopic handler. < 3 to > 10 tonne machine with diesel engine of 35–120 kW. Energy consumption varies from < 20 to > 500 kWh per day (equivalent to < 7 to > 150 L diesel).

### Decarbonisation pathways:

All technologies offering pathways to decarbonisation will need to be applied to cover the wide range of use cases and energy carriers available in different locations. Low carbon liquid or gaseous fuels, moving to renewable fuels are suitable for high-intensity use over long periods. Battery electric is viable for lower-intensity short use where electricity is available onsite. Renewable gaseous fuels including hydrogen are also feasible where production and distribution networks are available.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="60"/>	High
Work intensity	Low	<input type="range" value="60"/>	High
Type of use	Sporadic	<input type="range" value="60"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="60"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="40"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="60"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="40"/>	Short
Required machine mobility	Low	<input type="range" value="80"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="60"/>	Fast

## Example 3: Warehouses and distribution hub management

### Use description:

Moving goods around warehouses and loading and unloading trucks and vans, working continuously at 25% intensity.

### Machine employed:

Forklift truck with a **35 kW** engine using diesel or LPG, or battery electric using removable battery packs. Energy consumption of around **200 kWh** per day.

### Decarbonisation pathways:

Battery electric is a feasible solution if using interchangeable battery packs and off-vehicle charging stations, or when there are other vehicles to take their place while they are being charged. Hydrogen fuel cells could be used with onboard tanks depending on the availability of onsite hydrogen refill stations.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Availability of electricity on site	Available		Not available
Predictability of deployment	Pre-planned		Un-planned
Location of site	Adjacent to infrastructure		Remote from infrastructure
Time on site	Extended		Short
Required machine mobility	Low		High
Minimise refuelling/recharging	Infrequent		Fast

## Example 4: Refrigeration of trailer units

### Use description:

The refrigeration unit keeps the contents of the trailer at the required temperature such as -20°C. The trailer may be parked for extended periods, sometimes in remote locations. The unit will start and stop based on the temperature inside the trailer.

### Machine employed:

Diesel engine powered refrigeration unit. Engine powers range from **10–25 kW**. Plug in direct electric units are also used (where electricity supply is available) as well as hybrid versions.

### Decarbonisation pathways:

Diesel and hybrid versions can use low carbon fuels, moving to renewable fuels. Plug-in direct electric can use renewable electricity. Batteries could be used for short/medium distance journeys, recharged by regenerative braking or solar panels



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="50"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="80"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="80"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="20"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="50"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="75"/>	Short
Required machine mobility*	Low	<input type="range" value="50"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="80"/>	Fast

\*Including the trailer refrigeration unit.

# Mobile Generators

## Example 1: Prime power for small music festival or sporting event

### Use description:

The provision of 24-hour power for outdoor events in off-grid locations with average electricity demand of 150 kW and peak demand of 400 kW.

### Machine employed:

500 kVA ICE mobile generator. Producing 3.6 MWh of electricity per day. Using 1,000 L of diesel.

### Decarbonisation pathways:

Low carbon liquid or gaseous fuels transitioning to renewable fuels, including hydrogen.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Availability of electricity on site	Available	<b>Not available</b>	Not available
Predictability of deployment	Pre-planned		Un-planned
Location of site	Adjacent to infrastructure		Remote from infrastructure
Time on site	Extended		Short
Required machine mobility	Low		High
Minimise refuelling/recharging	Infrequent		Fast

## Example 2: Electrical power for small site facilities

### Use description:

Provision of electricity on smaller sites. Average demand of 10 kW with a peak demand of 75 kW.

### Machine employed:

Hybrid mobile generator with **25 kW** engine and battery pack modules of **20 kWh**. Energy consumption of approximately **200 kWh** (equivalent to **60 L** diesel) per day.

### Decarbonisation pathways:

Low carbon liquid and gaseous fuels moving to renewable fuels, including hydrogen. Fuel cells could provide efficient generation when running at low loads, with batteries providing peak power.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Availability of electricity on site	Available	<b>Not available</b>	Not available
Predictability of deployment	Pre-planned		Un-planned
Location of site	Adjacent to infrastructure		Remote from infrastructure
Time on site	Extended		Short
Required machine mobility	Low		High
Minimise refuelling/recharging	Infrequent		Fast

### Example 3: Electrical power for low level power demand in urban settings

**Use description:**

Provision of electricity to low demand sites, using less than about 50 kWh per day.

**Machine employed:**

50 kWh battery pack. Battery packs are swapped daily and charged offsite.

**Decarbonisation pathways:**

Use renewable electricity to charge battery packs.



**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="15"/>	High
Work intensity	Low	<input type="range" value="15"/>	High
Type of use	Sporadic	<input type="range" value="15"/>	Continuous
Availability of electricity on site	Available	<b>Not available</b>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="85"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="85"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="85"/>	Short
Required machine mobility	Low	<input type="range" value="15"/>	High
Minimise refuelling/recharging	Infrequent	<input type="range" value="15"/>	Fast

## Conclusion

The wide range of machines employed in this sector are often high-powered and used intensively in remote and rural areas, consuming large amounts of energy.

This energy, or fuel, is almost universally taken to the machine at its place of work. Some machines work less intensively on sites where electricity infrastructure exists and may be able to use electric powertrain solutions. Policy and regulation needs to be technology-neutral, and acknowledge these diverse requirements.

The benefits of different energy converters and energy carriers for decarbonisation need to be measured by assessing their respective carbon footprint using a Life Cycle Analysis (LCA) methodology.



# Forestry, Lawn and Utility Machines

This sector spans a diverse mix of machines, applications and uses for maintaining our green spaces and forests, and a multitude of smaller tasks in industry, construction and agriculture. The machines covered in this sector are largely hand held or hand moved. Larger machines, such as timber harvesters, are covered in other sectors such as NRMM. It makes a key contribution to the EU's biodiversity strategy<sup>8</sup> and targets for a sustainable built environment and sustainable rural development<sup>9</sup>.

**Forestry** includes handheld equipment such as pole pruners, brush cutters and chainsaws for applications such as reforestation and stock maintenance. This includes machines for professional use with 3-10 hour daily runtimes in remote off-grid forest environments accessible only by foot where workers must be able to carry a day's worth of fuel to the site by hand. The sector also covers machines for personal use running intermittently and used sporadically for a maximum of 2-3 hours, usually close to electric grid infrastructure.

**Lawn and Garden** encompasses machines that maintain our natural and green areas such as lawn mowers, chainsaws, hedge trimmers, and brush cutters. The sector ranges from machines for personal use operated intermittently with lower daily runtimes mostly in urban environments, to professional equipment operated continuously with moderate runtimes, often in remote locations.

**Utility** covers a broad mix of small industrial, construction and agricultural machinery predominantly for professional use, from concrete drills, saws and cut off saws to pumps, generators, handheld harvesters and earth augers. These machines need to run continuously, often in harsh conditions, across both populated and remote areas where fuel must be brought to the site.

The sector includes both handheld and non-handheld machines used for everything from light-to heavy-duty operations. These range from earth augers for gardening to concrete cutters for big infrastructure projects, drills for house building and water pumps for flood rescue.

These examples do not represent the only pathways to decarbonisation for each type of machine and each of these machines may require different powertrain technologies for different use cases. The upfront investment and operating costs of products for the forestry, turf and utility industries have a significant impact on the profitability of the use cases.

The energy consumption numbers in the following examples include the efficiency of the ICE, i.e. they are comparable to the output of the electric motor of electric machines.

<sup>8</sup>European Union (No date) Biodiversity Strategy for 2030.  
<sup>9</sup>European Union (No date) Rural development.



## Evaluation Criteria\*

## Use Case Evaluation

<b>Energy use</b>	Low	Is a large amount of energy used for the example task?	High
<b>Work intensity</b>	Low	Is the average power the machine is working at a high percentage of its maximum output power?	High
<b>Type of use</b>	Sporadic	Is the machine running for a high proportion of the task duration, or for a small portion?	Continuous
<b>Availability of electricity on site</b>	Available	Is electricity at a usable voltage and power available at the site of use of the machine?	Not available
<b>Predictability of deployment</b>	Pre-planned	Can the task be planned well in advance, or is it required to act urgently depending on circumstances?	Un-planned
<b>Location of site</b>	Adjacent to infrastructure	Is the machine being used in an area with infrastructure and service availability or any area without these?	Remote from infrastructure
<b>Time on site</b>	Extended	Is the time a machine is on site short i.e. days or weeks, or long i.e. months or years?	Short
<b>Required refuelling /recharging</b>	Low	Is it important to be able to complete a task without refuelling/recharging?	High

\* List of criteria for evaluation of the use cases in the following examples.

# Forestry

## Example 1: Silvicultural measures to prevent forest fires

### Use description:

Creating fire breaks and protective strips in the forest to prevent forest fires from spreading. Predominantly used in remote woodland locations far from electric grid infrastructure. These machines are operated intermittently at medium- and high-intensity throughout the working day. Fuel must be carried to the worksite.

### Machines employed:

Clearing saws and brush cutters with petrol engines of **2-3 kW**. Typical fuel consumption of **5-10 L** per day (equivalent to a battery capacity of **10-20 kWh**.)

### Decarbonisation pathways:

ICEs running on low carbon fuels, moving to renewable liquid fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="85"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="95"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="95"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="50"/>	Short
Required refuelling /recharging	Low	<input type="range" value="85"/>	High

## Example 2: Sequential timber harvesting

### Use description:

Medium-and heavy-duty timber harvesting usually in remote forests where fuel must be carried to the site by hand. Machines are used continuously for the full working day.

### Machines employed:

Larger handheld chainsaws with petrol engines of **3 kW to 6 kW**. Typical fuel consumption of **10-20 L** per day (equivalent to a battery capacity of **20-40 kWh**).

### Decarbonisation pathways:

ICEs running on low carbon, moving to renewable, liquid fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of use	Sporadic	<input type="range" value="75"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="85"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="85"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="75"/>	Short
Required refuelling /recharging	Low	<input type="range" value="85"/>	High

### Example 3: Professional tree and young stock maintenance in forestry

#### Use description:

Newly planted and younger trees are pruned in managed forests. Machines are used at light-to mid-range intensities, in short durations throughout the working day. This is usually in remote forests and fuel is carried to the forest with the tools.

#### Machine employed:

Pole pruner with 1-2 kW petrol engine. Fuel consumption is typically 1-2.5 L per day (equivalent to a battery capacity of 2-5 kWh).

#### Decarbonisation pathways:

Battery electric is viable if charging infrastructure is next to working place. ICEs running on liquid low carbon fuels, moving to renewable fuels are needed for higher intensity use over longer durations or in locations without charging infrastructure.



#### Evaluation Criteria

#### Use Case Evaluation

Energy use	Low	<input type="range" value="20"/>	High
Work intensity	Low	<input type="range" value="80"/>	High
Type of use	Sporadic	<input type="range" value="20"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="80"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="30"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="80"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="70"/>	Short
Required refuelling /recharging	Low	<input type="range" value="30"/>	High

## Example 4: Power lines clearing, maintenance of roads and railways in forestry

### Use description:

For clearing young trees beneath power lines and clearing vegetation around roads and railways for maintenance. Machines are used for short periods or continuously in medium- and heavy-duty operations, often in remote locations. Fuel is taken to the work site to last for a whole day's work.

### Machines employed:

Brush cutters, clearing saws and strimmers with **2-3 kW** petrol engines. Typical fuel consumption is **4-10 L** (equivalent to a battery capacity of **8-20 kWh**) per day.

### Decarbonisation pathways:

ICEs running on low carbon fuels, moving to renewable liquid fuels is the most practical pathway.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="70"/>	High
Work intensity	Low	<input type="range" value="85"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="85"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="30"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="85"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="85"/>	Short
Required refuelling /recharging	Low	<input type="range" value="85"/>	High

# Lawn

## Example 1: Lawncare in private gardens

### Use description:

Grass cutting and other lawncare work in private gardens, in developed or urban locations. They are used in both short and longer spells and for light- and medium-intensity operations.

### Machines employed:

Mowers, edge trimmers, trimmers, aerators, scarifiers with 1-2.5 kW petrol engines. Fuel consumption is typically of 0.2-2 L per day (equivalent to a battery capacity of 0.4-4 kWh).

### Decarbonisation pathways:

Battery electric solutions can be deployed for shorter low- and medium-duty use in locations where recharging is practical. The speed of the transition to battery electric is mainly affected by economic considerations.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="10"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="10"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="10"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="20"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="10"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="40"/>	Short
Required refuelling /recharging	Low	<input type="range" value="10"/>	High

## Example 2: Lawncare in municipal spaces, sports grounds, parks

### Use description:

A variety of lawncare tasks using varying degrees of intensity including heavy-duty tasks, typically for 8 hours a day and often in remote locations.

### Machines employed:

Mowers, aerators, scarifiers, rollers with 10–45 kW engines using petrol or diesel. Fuel consumption is typically 6L–38 L per day (equivalent to a battery capacity of 12–76 kWh).

### Decarbonisation pathways:

ICEs running on low carbon fuels, moving to renewable fuels for heavier duty and longer duration uses and for uses on remote sites. Battery electric can be used in light-intensity applications where the weight of batteries can be accommodated within machine designs and electricity is available for recharging.



### Evaluation Criteria

### Use Case Evaluation

Evaluation Criteria	Low	Use Case Evaluation	High
Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Availability of electricity on site	Available		Not available
Predictability of deployment	Pre-planned		Un-planned
Location of site	Adjacent to infrastructure		Remote from infrastructure
Time on site	Extended		Short
Required refuelling /recharging	Low		High

### Example 3: Professional tree services for private gardens, parks and public places

#### Use description:

Pruning, reducing and felling of trees in gardens, municipal parks and other public places. Intensity varies from low to high and machines are used from 1-8 hours per day. Locations are often urban and developed but may be remote.

#### Machines employed:

Chainsaws and trimmers with 1-2 kW petrol engines. Fuel consumption is typically 1 L-4 L per day (equivalent to a battery capacity of 2-8 kWh).

#### Decarbonisation pathways:

Battery electric is viable in operating environments with electric infrastructure. ICEs using low carbon fuels, moving to renewable fuels are required in other worksites.



#### Evaluation Criteria

#### Use Case Evaluation

Energy use	Low	<input type="range" value="25"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of use	Sporadic	<input type="range" value="50"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="25"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="25"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="50"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="75"/>	Short
Required refuelling /recharging	Low	<input type="range" value="50"/>	High

# Utility

## Example 1: Rail cutting

### Use description:

For railway maintenance, sections of rail are replaced when worn or distorted. A rail saw is used. This involves medium- to heavy-duty use for short to intermediate periods, often in remote locations without electric grid or charging infrastructure.

### Machine employed:

Cutting saw with **3 kW to 6 kW** petrol engine consuming around **4-10 L** of fuel a day (equivalent to a battery capacity of **8-20 kWh**).

### Decarbonisation pathways:

ICEs running on low carbon, moving to renewable liquid fuel is the most practical pathway. Battery electric may be feasible for light-medium duty use for short times (battery capacity being limited by the size and weight of the saw) and where charging infrastructure is available next to the jobsite.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="80"/>	High
Work intensity	Low	<input type="range" value="80"/>	High
Type of use	Sporadic	<input type="range" value="20"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="80"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="80"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="80"/>	Short
Required refuelling /recharging	Low	<input type="range" value="80"/>	High

## Example 2: Cutting concrete and asphalt

### Use description:

Cutting concrete and asphalt paving to separate areas for replacement or repair. Thicker sections require large cutting discs and higher drive power. Medium- and heavy-duty operations over short to moderate durations. They are often used in remote locations with little to no electric grid or charging infrastructure.

### Machine employed:

Circular saw/cut-off machines powered by petrol or diesel engine of **3-30 kW**. Fuel consumption is typically **2-30 L** per day (equivalent battery capacity of **4-60 kWh**).

### Decarbonisation pathways:

ICEs running on low carbon fuels and then renewable fuels is the most practical decarbonisation pathway. Medium-duty, short term operations may be able to use battery electric systems depending on the availability of nearby charging infrastructure.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="80"/>	High
Work intensity	Low	<input type="range" value="70"/>	High
Type of use	Sporadic	<input type="range" value="30"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="85"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="80"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="75"/>	Short
Required refuelling /recharging	Low	<input type="range" value="60"/>	High

### Example 3: Special saws for rescue operations

#### Use description:

Rapid cutting through metal and other materials to rescue people trapped after accidents such as vehicle crashes. 4-5 kW rescue saws for medium-to heavy-duty use over short periods in emergency scenarios such as train accidents. They are used for emergencies often in off-grid locations.

#### Machine employed:

Rescue saws with 4-5 kW engines running on petrol. Fuel consumption is typically 2-3 L per day (or an equivalent battery capacity of 4-6 kWh).

#### Decarbonisation pathways:

Battery electric is viable for short, medium intensity use, but heavy-duty operations over longer timespans may require ICEs running on low carbon fuels, moving to renewable fuels.



#### Evaluation Criteria

#### Use Case Evaluation

Energy use	Low	<input type="range" value="30"/>	High
Work intensity	Low	<input type="range" value="70"/>	High
Type of use	Sporadic	<input type="range" value="10"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="80"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="70"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="60"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="70"/>	Short
Required refuelling /recharging	Low	<input type="range" value="30"/>	High

## Example 4: Small machines for house construction

### Use description:

Various tasks involved in house building such as sawing and forming wood, cutting bricks and blocks. Handheld or hand moved machines, usually operating for short times with medium power requirements in urban areas that typically have infrastructure for electrification.

### Machines employed:

Chainsaws, circular saws, masonry cutters. Using 1-2 kW petrol engines. Fuel consumption is typically 0.1-2 L per day (equivalent to battery capacity of 0.2-4 kWh).

### Decarbonisation pathways:

Battery electric is viable for short, medium intensity use, but heavy-duty operations over longer timespans may require ICEs running on low carbon and then renewable fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="30"/>	High
Work intensity	Low	<input type="range" value="80"/>	High
Type of use	Sporadic	<input type="range" value="10"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="40"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="40"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="50"/>	Short
Required refuelling /recharging	Low	<input type="range" value="30"/>	High

## Example 5: Olive harvesting

### Use description:

Harvesting olive groves usually in remote areas with fuel carried to the jobsite by hand. The machine is used for round-the-clock operations at medium intensity.

### Machine employed:

Special purpose olive harvester with 1.5–2.5 kW petrol engine. Fuel consumption typically 1–2.5 L per day (equivalent to a battery capacity of 2–5 kWh).

### Decarbonisation pathways:

Battery electric is viable if charging infrastructure is next to the jobsite. Liquid low carbon fuels, moving to renewable fuels are needed for higher intensity use over longer durations or in locations without charging infrastructure.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Availability of electricity on site	Available		Not available
Predictability of deployment	Pre-planned		Un-planned
Location of site	Adjacent to infrastructure		Remote from infrastructure
Time on site	Extended		Short
Required refuelling /recharging	Low		High

## Example 6: Mobile water pump

### Use description:

Water pump for use on construction sites, farms and for flood alleviation.

### Machine employed:

100–150 mm bore pump with 10–15 kW diesel engine. Petrol engines can also be used. Electric version can be used if power is available onsite, or coupled to a small generator.

### Decarbonisation pathways:

ICEs running on low carbon fuels, moving to renewable fuels. Renewable electricity for electric version.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="80"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="80"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="80"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Location of site	Adjacent to infrastructure	<input type="range" value="80"/>	Remote from infrastructure
Time on site	Extended	<input type="range" value="80"/>	Short
Required refuelling /recharging	Low	<input type="range" value="80"/>	High

## Conclusion

The machines used in this sector are lower powered and often handheld or moved by hand. Use cases vary widely from occasional domestic use to high-intensity long-duration use in remote locations, when fuel must be carried to the site with the machine. Battery electric powertrains are potentially viable for lighter use, short-duration work where recharging is feasible, but internal combustion engines using energy-dense liquid fuels will be required for higher intensity, longer duration work in remote locations. A tenfold increase in the gravimetric energy density of the battery pack would be needed to maintain usage patterns for machines that are mainly used in remote locations with high operating times for extended periods.

The upfront investment and operating costs of products and charging solutions for the forestry, turf and utility industries have a significant impact on the profitability of the use cases. This is particularly important for small companies and individual professional users that earn their money through these tasks and tend to be in the lower wage segment. Battery-electric drives, including the required batteries and charging infrastructure, usually result in significantly higher initial investments for these companies. Therefore, beyond considering technical feasibility, additional measures will be needed to significantly improve the cost-effectiveness of products that drive decarbonisation.

Policymakers need to recognise this diverse array of requirements and take a technology-neutral approach to decarbonisation. The decarbonisation potential of low carbon and renewable fuels should be measured using a holistic LCA assessment, and this methodology needs to be included in policy.



# Marine Inland Waterways Transport

European inland waterways transport is one of the key arteries of Europe's trade and one of the lowest carbon forms of transport, consuming just 17% of the energy of road transport and 50% less than rail.<sup>10</sup> Its largest route is the River Rhine and its tributaries, but it also encompasses some 41,000 km of EU waterways linking cities and industrial regions and extends beyond EU boundaries to Switzerland. Whilst some vessels are part of company-owned fleets, many are individually/family owned by the vessel operator.

The sector faces challenging economic conditions and includes many small family businesses. Decarbonisation pathways will need to be commercially viable to lower barriers to adoption. This will require a multifaceted approach, factoring in the specific economic conditions of this sector and long vessel lifespans averaging 30 years. The sector is also very diverse with widely varying boat sizes, applications and operations. These range from small general-purpose craft to large cruise and cargo ships, with both fixed itineraries and flexible routes adapted to market demand, requiring a high degree of operational flexibility.

Refuelling is traditionally done at bunker points before or after a journey, and some vessels need to store enough energy-dense fuel to last several days. Low carbon and renewable drop-in fuels can enable early decarbonisation, whilst other fuels such as methanol and hydrogen can be used in adapted engines. Fuel cells and battery electric may also be suitable for some vessels and journey types.

These examples do not represent the only pathways to decarbonisation for each type of vessel and each machine may require alternative powertrain technologies for different use cases.

The energy consumption numbers in the following examples include the efficiency of the ICE, i.e. they are comparable to the output of the electric motor of electric machines.

<sup>10</sup>European Commission (No date) Inland Waterways. Directorate-General for Mobility and Transport.



## Evaluation Criteria\*

## Use Case Evaluation

Energy use	Low	Is a large amount of energy used for the example task?	High
Work intensity	Low	Is the average power the vessel is working at a high percentage of its maximum output power?	High
Type of voyage	Stop-start	Does the vessel stop frequently or run continuously through the voyage?	Continuous
Predictability of voyage	Pre-planned	Is the journey planned well in advance, or is it required to change course during the voyage depending on circumstances?	Un-planned
Remoteness	Lake or river	Is the voyage over open seas or on a lake or river close to shore?	Open seas
Voyage duration	Low	Does the voyage last for many hours, days or weeks, or is it of short duration?	High

\*List of criteria for evaluation of the use cases in the following examples.

## Example 1: Transport of miscellaneous cargos on varied routes at short notice

### Use description:

Operators of general cargo vessels travel major river routes to a variety of destinations on short notice contracts making miscellaneous on-demand cargo deliveries.

### Vessel employed:

Shallow draft **5,000–20,000 tonne** general cargo vessel. Powered by diesel engines of **1–10 MW** and using between **1–10 tonnes** of fuel a day (equivalent to **5–50 MWh**.)

### Decarbonisation pathways:

Drop-in low carbon fuels (such as HVO) moving to renewable liquid fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of voyage	Stop-start		Continuous
Predictability of voyage	Pre-planned		Un-planned
Remoteness	Lake or river		Open seas
Voyage duration	Low		High

## Example 2: Shipment of 20 containers daily on fixed route

### Use description:

Daily shipment of containerised materials on a fixed 60 km route

### Vessel employed:

**90 metre** container ship with a capacity of **24 containers**. Powered by electric motors (**760 kW**) with **2 MWh** containerised and swappable battery packs.

### Decarbonisation pathways:

Battery packs are recharged using renewable electricity.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="10"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of voyage	Stop-start	<input type="range" value="50"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="10"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="10"/>	Open seas
Voyage duration	Low	<input type="range" value="10"/>	High

### Example 3: River ferry travelling a fixed route back and forth

**Use description:**

River ferry travelling a fixed route back and forth, unloading and loading at each quay. Using around 20 kWh of energy per journey. A similar use case is to cross lakes.

**Vessel employed:**

Small passenger and vehicle ferry using 100 kW diesel engine for propulsion.

**Decarbonisation pathways:**

Battery and electric motor with charging taking place whilst loading or unloading. Retain Internal Combustion Engines (ICEs) using drop-in low carbon fuels and renewable fuels.



**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="10"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of voyage	Stop-start	<input type="range" value="10"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="10"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="20"/>	Open seas
Voyage duration	Low	<input type="range" value="10"/>	High

## Conclusion

The technologies to decarbonise inland waterways transport are already available. However, successful adoption will require a transition period and sufficient lead time, for example, to facilitate development of the required enabling infrastructure of bunkering stations for low carbon and renewable fuels.

Any decarbonisation pathways need to reflect the sector's specific ownership structure.

European Inland Waterway vessels represent a relatively small market for powertrains. Alignment with international direction, policy and standards is therefore important.

Policy and regulation needs to be technology-neutral, and acknowledge the diverse requirements of Inland Waterways Transport. The benefits of different energy converters and energy carriers for decarbonisation need to be measured by assessing their respective carbon footprint using a Life Cycle Analysis (LCA) methodology, and this should be included in policy.



# Marine Seagoing

Marine seagoing is an international activity with vessels travelling across the world's oceans. World trade involves the shipment of large quantities of goods between continents. International standards and policies are generally governed by the United Nation's International Maritime Organisation (IMO). Alignment with the IMO regulatory framework requires a long-term approach due to its global scope and decision-making procedures. Regional provisions are also being developed. These include the EU Taxonomy, which includes climate change mitigation measures covering sea and coastal, freight and passenger transport, FuelEU Maritime introducing a stepwise reduction of fuel GHG-intensity, and the extension of the European Emission Trading System (ETS) to maritime transport.

The marine seagoing sector accounts for 3-4% of the EU's CO<sub>2</sub> emissions and approximately 3% of global CO<sub>2</sub> emissions.<sup>11</sup> Options for decarbonising this sector will need to account for a diverse array of vessels with widely varying energy needs, ranges and requirements. These encompass large ocean-going vessels at sea for weeks following either fixed or flexible routes, in-shore ships carrying goods short distances, or small ferries, workboats, auxiliary and emergency vessels.

For example, oceangoing container ships, tankers, bulk carriers or gas carriers either follow pre-planned routes or adapt their destinations to market trends and cargo availability, whereas tugboats may be used for in-harbour tasks or ocean duties.

Decarbonisation pathways will also depend on vessel refuelling needs including bunkering, infrastructure and delivery of fuel

to these facilities. Refuelling is traditionally done at bunker points before or after a journey. Large oceangoing vessels usually store energy-dense fuels for months, and less energy-dense alternative fuels such as ammonia or methanol may require bigger tank capacity or more frequent bunkering. Several studies find a limited potential of direct renewable energy and electrification meeting the energy needs of oceangoing vessels.<sup>12 13 14 15</sup>

Smaller ships on shorter routes could use less energy-dense fuels or electrification. Other considerations include the average lifetime of vessels and how retrofit options could help facilitate the use of low carbon and renewable fuels for the existing marine seagoing fleet.

These examples do not represent the only pathways to decarbonisation for each type of vessel and each of these vessels may require different powertrain technologies for different use cases.

The energy consumption numbers in the following examples include the efficiency of the ICE, i.e. they are comparable to the output of the electric motor of electric machines.



<sup>11</sup>European Commission (No date) Reducing Emissions from the Shipping Sector. Directorate-General for Climate Action. Energy, Climate change, Environment.

<sup>12</sup>International Energy Agency. (2023). Aviation and Shipping. DNV. (2024). Maritime Forecast to 2050.

<sup>13</sup>International Renewable Energy Agency. (2021). A Pathway to Decarbonise the Shipping Sector by 2050.

<sup>14</sup>Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021). Industry Transition Strategy.

<sup>15</sup>Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021). Battery-Powered Vessels Pre-Feasibility Study.



## Evaluation Criteria\*

## Use Case Evaluation

Evaluation Criteria*	Low	Use Case Evaluation	High
Energy use	Low	Is a large amount of energy used for the example task?	High
Work intensity	Low	Is the average power the vessel is working at a high percentage of its maximum output power?	High
Type of voyage	Stop-start	Does the vessel stop frequently or run continuously through the voyage?	Continuous
Predictability of voyage	Pre-planned	Is the journey planned well in advance, or is it required to change course during the voyage depending on circumstances?	Un-planned
Remoteness	Lake or river	Is the voyage over open seas or on a lake or river close to shore?	Open seas
Voyage duration	Low	Does the voyage last for many hours, days or weeks, or is it of short duration?	High

\*List of criteria for evaluation of the use cases in the following examples.

## Example 1: Transport of large quantities of containers from East Asia to Europe

### Use description:

The shipment of large quantities of containers from East Asia to Europe at lowest cost. Nonstop inter-continental travel (around 30 days). The largest vessels can carry 24,000 TEUs (20 ft container equivalents).

### Vessel employed:

**235,000 tonne** container ship with a **58.6 MW** single-fuel Internal Combustion Engine (ICE), that consumes around **220 tonnes** of fuel oil daily and can store **10,000 tonnes** of fuel oil. This has an energy content of around **60 GWh** at the propeller shaft (**157 g/kWh**).<sup>16</sup>

### Decarbonisation pathways:

High efficiency ICE using low carbon drop-in fuels such as biofuel or renewable fuels such as ammonia or methanol. Large bulk carriers and tankers have similar use cases and decarbonisation pathways.



<sup>16</sup>Maersk (2025) Vessel Particulars. ShipmentLink.

### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="80"/>	High
Work intensity	Low	<input type="range" value="70"/>	High
Type of voyage	Stop-start	<input type="range" value="85"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="10"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="80"/>	Open seas
Voyage duration	Low	<input type="range" value="80"/>	High

## Example 2: Ammonia tanker

### Use description:

Ships carrying ammonia, e.g. as renewable energy carrier, for intercontinental transport.

### Vessel employed:

The capacity of these ships can be over **90,000 m<sup>3</sup>** of liquid ammonia. These ships can use ICEs utilising their ammonia cargo as fuel. Image is of NoGAPS concept tanker.

### Decarbonisation pathways:

Progressively decarbonise the ammonia fuel, moving to renewable ammonia. These ships could carry renewable energy with ammonia as an energy carrier and would use ICEs utilising their ammonia cargo as fuel.



Picture: 3D rendering

### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of voyage	Stop-start	<input type="range" value="85"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="75"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="85"/>	Open seas
Voyage duration	Low	<input type="range" value="50"/>	High

### Example 3: Transporting timber from Sweden to UK

**Use description:**

Shipping bulk timber around 1,200 km from Sweden to UK. Non-stop journey of 2 days.

**Vessel employed:**

4,000 tonne general cargo vessel with a 1 MW diesel engine. The Vessel uses 20 MWh of energy per day (4 tonnes of fuel oil).

**Decarbonisation pathways:**

Low carbon and renewable fuels used in ICEs. Other bulk carriers have similar use cases and decarbonisation pathways.



**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low		High
Work intensity	Low		High
Type of voyage	Stop-start		Continuous
Predictability of voyage	Pre-planned		Un-planned
Remoteness	Lake or river		Open seas
Voyage duration	Low		High

### Example 4: Harbour ferry travelling a fixed route

**Use description:**

Harbour ferry travelling a fixed route of 2 km. Travels back and forth, unloading and loading at each quay. Consumes circa 20 kWh of energy per journey. Another similar use is crossing rivers and lakes.

**Vessel employed:**

Small passenger and vehicle ferry using 100 kW diesel engine for propulsion.

**Decarbonisation pathways:**

Battery and electric motor with charging whilst loading/unloading; retain ICE using drop-in low carbon fuels; ICE using renewable fuel.



**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="10"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of voyage	Stop-start	<input type="range" value="10"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="10"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="20"/>	Open seas
Voyage duration	Low	<input type="range" value="10"/>	High

## Example 5: Tugboat

### Use description:

Manoeuvring larger vessels in harbour and on open seas.

### Vessel employed:

**35 m, 300 tonne** hybrid diesel-electric tugboat. It uses electric-only propulsion in harbour, and diesel generators for open seas duties. The ship has two **1,000 kW** electric propulsion motors and a **2.5 MWh** battery, alongside two **1,000 kW** diesel engine generators. Energy consumption is typically around **10 MWh** a day for higher speed high load work at sea, or **2-4 MWh** per day in harbour.

### Decarbonisation pathways:

The battery can be recharged whilst moored using renewable electricity. The diesel engine can use low carbon fuel moving to renewable fuel.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of voyage	Stop-start		Continuous
Predictability of voyage	Pre-planned		Un-planned
Remoteness	Lake or river		Open seas
Voyage duration	Low		High

## Conclusion

Successful decarbonisation of the marine seagoing sector will require a broad, balanced technology-neutral approach to accommodate a diverse array of vessels, applications, and patterns of use.

Alternative solutions must be available at a large scale and future-proof to stay aligned with evolving international maritime frameworks such as the IMO, while ensuring continued cost-competitiveness and compatibility with the global maritime industry.

Policy support will be key to accelerate development and distribution of sustainable marine fuels and establish domestic supply chains and bunkering facilities for renewable fuels.

The technology is ready but deployment relies upon the availability of low carbon and renewable fuels at bunkering sites.



# Marine Recreational Craft

This industry encompasses a variety of recreational boats, primarily less than 24 m, used for purposes from fishing and water sports to cruising.<sup>17</sup> The fleet comprises a diverse mix of vessels from sailing and motor yachts, sports boats and tenders to emergency craft. Whilst the use of these vessels is predominantly private, they are sometimes used for professional purposes.

The recreational craft sector accounts for 0.4% of transportation emissions in Europe. Recreational craft have an average lifecycle of 30–50 years with a high proportion of old vessels still in service. Most boats are owned for occasional leisure use and used on average between 35 and 48 hours per year.<sup>18</sup>

Decarbonisation pathways must be broad and compatible with a rich variety of vessels of differing ages and user demands. New technologies will also need to provide equivalent safety, reliability and performance to conventional systems.

The decarbonisation of the recreational craft sector may result in a different usage pattern with respect to the distance travelled or performance, which customers need to be aware of. To maintain the current range of the vessels, low carbon and net zero carbon fuels with equivalent energy density to diesel or gasoline will be needed.

With such a low average use time, the environmental performance of the manufacturing process and choice of raw materials will play a significant role in the life cycle assessment of the recreational craft.

These examples do not represent the only routes to decarbonisation for each type of vessel and each vessel may require different powertrain technologies or energy carriers for different use cases.

The energy consumption numbers in the following examples include the efficiency of the ICE, i.e. they are comparable to the output of the electric motor of electric machines.

<sup>17</sup>European Union (2013) Directive 2013/53/EU of the European Parliament and of the Council of 20 November 2013 on Recreational Craft and Personal Watercraft and Repealing Directive 94/25/EC. EUR-Lex.

<sup>18</sup>RICARDO, ICOMIA (2023) Pathways to Propulsion Decarbonisation for the Recreational Marine Industry. Synopsis Report. © Ricardo plc 2023.



## Evaluation Criteria\*

## Use Case Evaluation

Energy use	Low	Is a large amount of energy used for the example task?	High
Work intensity	Low	Is the average power the vessel is working at a high percentage of its maximum output power?	High
Type of voyage	Stop-start	Does the vessel stop frequently or run continuously through the voyage?	Continuous
Predictability of voyage	Pre-planned	Is the journey planned well in advance, or is it required to change course during the voyage depending on circumstances?	Un-planned
Remoteness	Lake or river	Is the voyage over open seas or on a lake or river close to shore?	Open seas
Voyage duration	Low	Does the voyage last for many hours, days or weeks, or is it of short duration?	High

\*List of criteria for evaluation of the use cases in the following examples.

## Example 1: Ocean-going sailing yacht

### Use description:

Long distance voyages taking weeks and months. Propulsion is primarily from wind, though auxiliary engine power is required when becalmed, or in port.

### Vessel employed:

**15 metre** sailing yacht mainly propelled by wind with a **35 kW** inboard auxiliary engine. The engine is typically run continuously for several days consuming around **200 L** of diesel (**700 kWh**).

### Decarbonisation pathways:

Replacing diesel with renewable fuels in existing ICEs would maintain range and performance. Batteries of the capacity needed to power a boat of this size and weight would reduce range by circa 90%<sup>19</sup> and require a system such as a solar PV generator to maintain state of charge.



<sup>19</sup>RICARDO, ICOMIA (2023) Pathways to Propulsion Decarbonisation for the Recreational Marine Industry. Synopsis Report. © Ricardo plc 2023.

### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of voyage	Stop-start	<input type="range" value="75"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="75"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="75"/>	Open seas
Voyage duration	Low	<input type="range" value="75"/>	High

## Example 2: Motor cruiser for offshore cruising

### Use description:

Offshore cruising in the Mediterranean or other seas. Several days at sea per voyage leg. Shorter, inshore trips are also often undertaken.

### Vessel employed:

**12 metre** motor cruiser with **2 x 250 kW** diesel engines. It has an **800 L** fuel tank (equivalent to a battery capacity of **3 MWh**) with a range of **1,000 km** and consumes an average of **250 L** of diesel per offshore journey (**1 MWh**).

### Decarbonisation pathways:

Low carbon, moving to renewable, liquid fuels. The reduction in battery size needed due to weight, cost and space constraints would reduce vessel range by 80%.<sup>20</sup>



<sup>20</sup>RICARDO, ICOMIA (2023) Pathways to Propulsion Decarbonisation for the Recreational Marine Industry. Synopsis Report. © Ricardo plc 2023.

### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of voyage	Stop-start		Continuous
Predictability of voyage	Pre-planned		Un-planned
Remoteness	Lake or river		Open seas
Voyage duration	Low		High

### Example 3: Roaming tender for short in-harbour journeys

**Use description:**

Short journeys to ferry passengers and goods between anchored boats in harbour and shore. Each journey is usually short (circa 15 minutes) with additional loading, unloading and idle time.

**Vessel employed:**

6 metre boat with 45 kW propulsion power. Energy used circa 15 L diesel (45 kWh) per day.

**Decarbonisation pathways:**

Internal Combustion Engine (ICE) with low carbon moving to renewable fuel. Battery electric or hydrogen fuel cells are also viable options.<sup>21</sup>



<sup>21</sup>RICARDO, ICOMIA (2023) Pathways to Propulsion Decarbonisation for the Recreational Marine Industry. Synopsis Report. © Ricardo plc 2023.

**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="10"/>	High
Work intensity	Low	<input type="range" value="10"/>	High
Type of voyage	Stop-start	<input type="range" value="10"/>	Continuous
Predictability of voyage	Pre-planned	<input type="range" value="80"/>	Un-planned
Remoteness	Lake or river	<input type="range" value="10"/>	Open seas
Voyage duration	Low	<input type="range" value="10"/>	High

## Conclusion

There is no one-size-fits-all solution to decarbonise a wide range of boats of varying sizes, ages and use patterns. The decarbonisation pathways must reflect the long average life cycles of recreational craft and the fact that a large proportion of older vessels are still in use.

Policymakers should avoid prescribing specific pathways to decarbonise. Instead, they should focus on creating an ecosystem which enables availability of all energy carriers from electric grid and charging infrastructure to production and supply of low-and zero-carbon fuels, alongside bunkering facilities at marinas.

Policy should to recognise the decarbonisation potential of low carbon and renewable fuels. A life cycle methodology (LCA method) for assessment of carbon emissions needs to be used for all energy converters and energy carriers.

Consumer safety and government bodies could also work closely with industry to establish marine electric technology standards and consumer safety protocols.

Additionally, consumer education campaigns could facilitate and accelerate the acceptance and uptake of new renewable fuels.



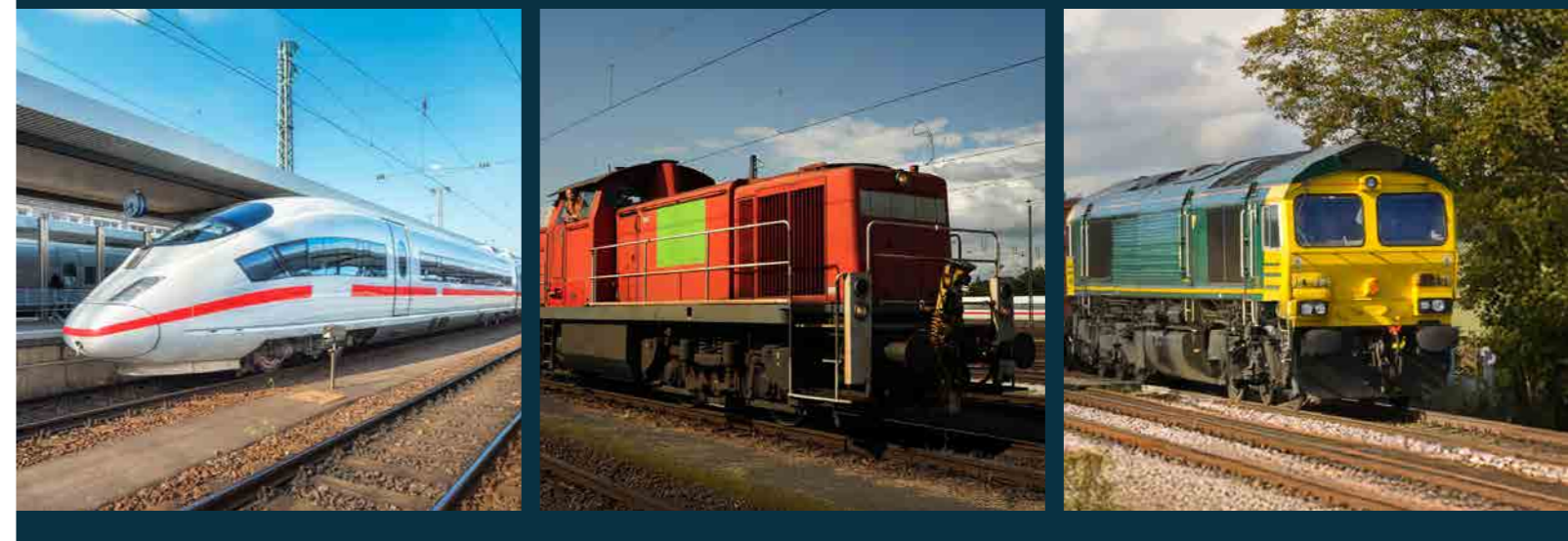
# Rail Transport

Europe’s rail transport network accounts for just 0.4% of Europe’s total transport GHG<sup>22</sup> emissions and is already widely electrified with electric trains comprising 54% of the network and 80% of all passenger kilometres travelled. Yet, further rail electrification would involve high infrastructure costs primarily for smaller, less-travelled<sup>23</sup> routes such as freight-only tracks, secondary and branch lines. Onboard batteries are currently not used for applications such as long-range heavy haul rail.

Trains running on non-electric routes or across a mix of electric and non-electric lines are currently diesel powered. Low carbon and renewable fuels, and bi-mode powertrains with the versatility to run on electric and non-electric tracks could help decarbonise this format of rail network.

Alternative solutions for rail transport must fulfil the requirement for interoperability, cost-efficiency, range, reliability, and safety across a mixture of track types, trains and diverse use cases from shunting to freight transport.

The following examples are not the only pathways to decarbonisation for each type of vehicle and machine.



## Evaluation Criteria\*

## Use Case Evaluation

Energy use	Low	Is a large amount of energy used for the example task?	High
Work intensity	Low	Is the average power the machine is working at a high percentage of its maximum output power?	High
Type of use	Sporadic	Is the machine running for a high proportion of the task duration, or for a small portion?	Continuous
Availability of electricity on site	Available	Is electricity at a usable voltage and power available at the site of use of the machine?	Not available
Predictability of deployment	Pre-planned	Can the task be planned well in advance, or is it required to act urgently depending on circumstances?	Un-planned
Minimise refuelling/recharging	Infrequent	Is it important to be able to complete a task without refuelling/recharging?	Fast

\*List of criteria for evaluation of the use cases in the following examples.

<sup>22</sup>UNIFE (2024) On the Move to a net zero EU: The European Rail Supply Industry Priorities for 2024-2029.

<sup>23</sup>European Commission (No date) European Alternative Fuels Observatory. Rail: Electrification of Rail Infrastructure. Directorate-General for Mobility and Transport.

## Example 1: Passenger travel on electrified mainline routes

### Use description:

People commuting or travelling for business or leisure on mainline rail routes. There is a comprehensive network of major rail lines throughout Europe. Individual trains typically run for 16-20 hours a day.

### Vehicle employed:

Electric train with direct electric supply and 32 **500 kW** electric motors (**16 MW** total). High load factor when running near maximum speed.

### Decarbonisation pathways:

Progressive decarbonisation of the electricity supply.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="85"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="15"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="15"/>	Un-planned
Minimise refuelling/recharging	Infrequent	<input type="range" value="85"/>	Fast

## Example 2: Freight transport between industrial and commercial centres on a non-electrified network

### Use description:

Transporting large consignments of diverse goods between industrial centres and logistics hubs using some mainline and some freight specific tracks, which are not usually electrified. Load factors are high when the train is fully laden. Train speeds are lower than passenger services and journeys take many hours (or days). A large train could consume 15 MWh of energy on a 10-hour journey.

### Vehicle employed:

Train consisting of high-power locomotive(s) and multiple freight carriages. Up to **750 metres** in length and weighs circa **4,000 tonnes** in Europe. Locomotives use Internal Combustion Engines (ICE) up to circa **3,000 kW**.

### Decarbonisation pathways:

As electrification of the complete track network is not regarded as economically feasible, continuing use of ICEs is expected. Decarbonisation is achieved through use of low carbon fuels, and then renewable fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of use	Sporadic	<input type="range" value="85"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="75"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="50"/>	Un-planned
Minimise refuelling/recharging	Infrequent	<input type="range" value="85"/>	Fast

### Example 3: Regional passenger travel

**Use description:**

People travelling for business or leisure between towns or cities using main and branch lines that are electrified in parts. Journeys are typically 1 to 3 hours and trains may be lightly or more heavily occupied.

**Vehicle employed:**

Railcars with electric or ICE propulsion. Bi-mode vehicles with electric motors can run on direct electricity supply via catenary, or from diesel generators when using non-electrified tracks. Such trains use multiple ICE engines of typically **300–800 kW**. Hybrid ICE/battery electric propulsion can provide efficiency benefits from recuperation and can run in pure electric mode for limited periods such as when in stations. A direct electric propulsion system, with battery backup, is feasible where non-electrified sections of track are short. The diesel generator can be replaced with a fuel cell and battery.

**Decarbonisation pathways:**

ICEs can run on low carbon, moving to renewable fuels. Direct electricity supply from the grid can be progressively decarbonised. Renewable hydrogen can be used with the ICE or fuel cell electric version.



Picture: 3D rendering

**Evaluation Criteria**

**Use Case Evaluation**

Energy use	Low	<input type="range" value="50"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="75"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="50"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="25"/>	Un-planned
Minimise refuelling/recharging	Infrequent	<input type="range" value="50"/>	Fast

## Example 4: Regional freight transport

### Use description:

Transport of a variety of goods between regional distribution centres and industrial users. A mixture of electrified and non-electrified tracks is used.

### Vehicle employed:

Medium-sized diesel locomotive of **1,000–2,500 kW**. Bi-Mode locomotives (ICE/Electric) can switch to electric operation on electrified lines. Lines with shorter unelectrified sections could also use (battery/direct electric) Bi-Mode systems.

### Decarbonisation pathways:

ICEs can run on low carbon, moving to renewable fuels. Direct electricity supply from the grid can be progressively decarbonised.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="60"/>	High
Work intensity	Low	<input type="range" value="50"/>	High
Type of use	Sporadic	<input type="range" value="75"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="50"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="20"/>	Un-planned
Minimise refuelling/recharging	Infrequent	<input type="range" value="70"/>	Fast

## Example 5: Shunting rolling stock in depots and sidings

### Use description:

Moving of rolling stock in depots and sidings, travelling short distances at low speeds. High tractive effort is required. Shunters will often work in or from a designated depot, and energy consumption for each task is usually quite low. The power of smaller shunters ranges from 200-500 kW while larger ones reach up to 1,800 kW.

### Vehicle employed:

**25 tonne** shunting locomotive.  
**200 kW** motors and **250 kWh** battery.

### Decarbonisation pathways:

Battery electric powertrains use reduced carbon electricity supply for charging. Diesel-Electric and hybrid powertrains, used for higher power and greater range, can be decarbonised by using low carbon or renewable fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="10"/>	High
Work intensity	Low	<input type="range" value="80"/>	High
Type of use	Sporadic	<input type="range" value="50"/>	Continuous
Availability of electricity on site	Available	<input type="range" value="50"/>	Not available
Predictability of deployment	Pre-planned	<input type="range" value="80"/>	Un-planned
Minimise refuelling/recharging	Infrequent	<input type="range" value="10"/>	Fast

## Conclusion

Rail transport has made significant progress decarbonising its energy use and is already a leading transport sector in this regard. The industry has developed and implemented widespread electrification alongside low carbon fuels where ICEs are still used. Much of the European rail network is already supplied by electricity directly through catenary structures.

Some less-used lines do not warrant the high cost of electric infrastructure and require other decarbonisation solutions. The full range of powertrain technologies is expected to be required, depending on required use patterns and the availability of low carbon and renewable energy carriers.

Policy should reflect these widely varying demands and avoid specifying particular decarbonisation pathways. Energy carriers need to be assessed on a life cycle basis (LCA) to recognise the decarbonisation potential of low carbon and renewable fuels.



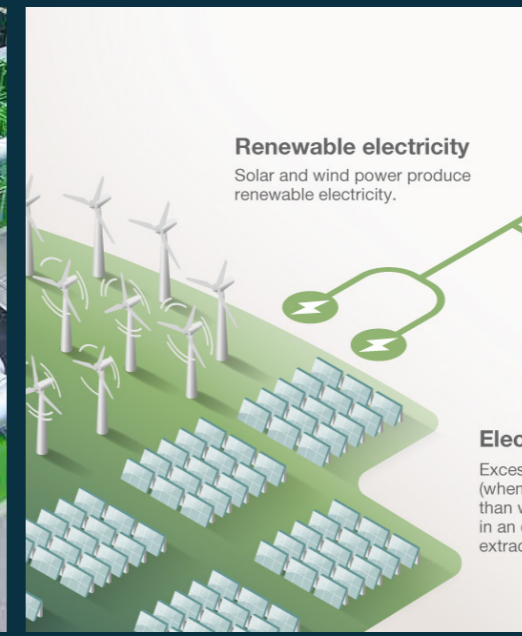
# Stationary Power Plants

Reciprocating Internal Combustion Engines (RICEs) are used in power plants, predominantly for electrical power generation. The heat from the engine can also be utilised in Combined Heat and Power (CHP) installations. The electrical energy produced can be used as prime supply for off-grid consumers, as part of a grid system, or for example to balance fluctuations in renewable generation and support rapid changes in electricity consumption. RICE plants are also used as emergency backup power generators where other provision fails, such as in hospitals. Power outputs for these units can reach up to 20 MW and installations may encompass multiple engines with a combined power of up to 500 MW. Smaller stationary engines in the range of 0.1 - 1.5 MW may also be used to drive emergency water pumps for building fire suppression when the grid fails.

As the proportion of intermittent renewable power generation increases, grid reliability or power availability becomes more challenging. The need for dispatchable generating capacity that can be rapidly deployed and is not dependent on uncontrolled factors (such as wind and sun) becomes more critical. This is provided by internal combustion engines as they have fast start-ups and quickly respond to changes in load demand.

Today, these units operate on heavy or light fuel oil, natural gas, or liquid or gaseous biofuels and even H<sub>2</sub>/NG blends up to 25% by volume. Europe's accelerating transition to renewable power generation will see a reduced role for base load power plants but require an increased role for grid support. New power plant engines are now being developed to use hydrogen, ammonia, methanol and other renewable fuels such as e-Diesel and e-Methanol. Dual fuel engine versions are also already available or in development improving fuel security/flexibility. Excess heat from the engines can be used, for example, for district heating with combined heat and power offering heat and electricity from the same source and achieving a very high total fuel utilisation rate of 90% or more.

It is, however, important to note that these examples do not cover all the pathways for decarbonisation of engine power plants and a specific case may require different engine configurations.



## Evaluation Criteria\*

## Use Case Evaluation

Evaluation Criteria*	Low	Use Case Evaluation	High
<b>Energy use</b>	Low	Is a large amount of energy used for the example task?	High
<b>Work intensity</b>	Low	Is the average power the engine is working at a high percentage of its maximum output power?	High
<b>Type of use</b>	Sporadic	Is the engine running for a high proportion of the task duration, or for a small portion?	Continuous
<b>Predictability of deployment</b>	Pre-planned	Can the task be planned well in advance, or is it required to act urgently depending on circumstances?	Un-planned
<b>Time on site</b>	Extended	Is the time an engine is on site short i.e. days or weeks, or long i.e. months or years?	Short

\*Terms used to explain the use case evaluations found in the following examples.

## Example 1: Microgrid for remote rural communities or individual facilities

### Use description:

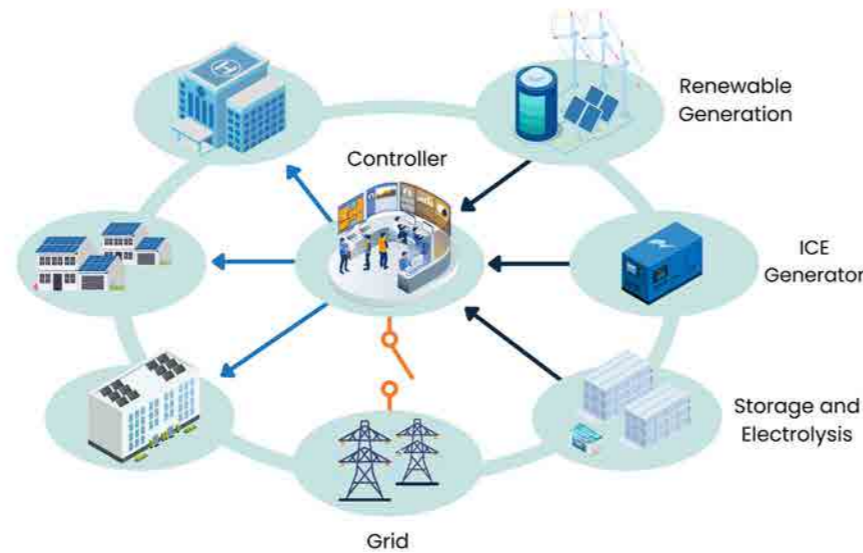
A smaller electrical generating and distribution system for an isolated small town, island or rural area, industrial facility, or data centre. Reciprocating Internal Combustion Engine (RICE) generators are used and can be supplemented with renewable generation.

### System employed:

RICE generator plant of 1-20 MW output size operating on gaseous or liquid fuels. The microgrid could use renewable baseload generation by wind and solar, balanced with an RICE using low carbon fuels, moving to renewable, gaseous or liquid fuels.

### Decarbonisation pathways:

Low carbon fuels, moving to renewable, gaseous and liquid fuels. This includes hydrogen, ammonia and e-Methanol, as well as fuels of biological origin. The microgrid could use renewable base load generation by wind and solar, balanced with an RICE generator. This could be supported with short-term battery storage, or with longer term surplus generation stored chemically as hydrogen or e-Fuels. The heat from the engines may also be used for building heating where this is feasible.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Predictability of deployment	Pre-planned		Un-planned
Time on site	Extended		Short

## Example 2: Main grid support in renewable generation systems

### Use description:

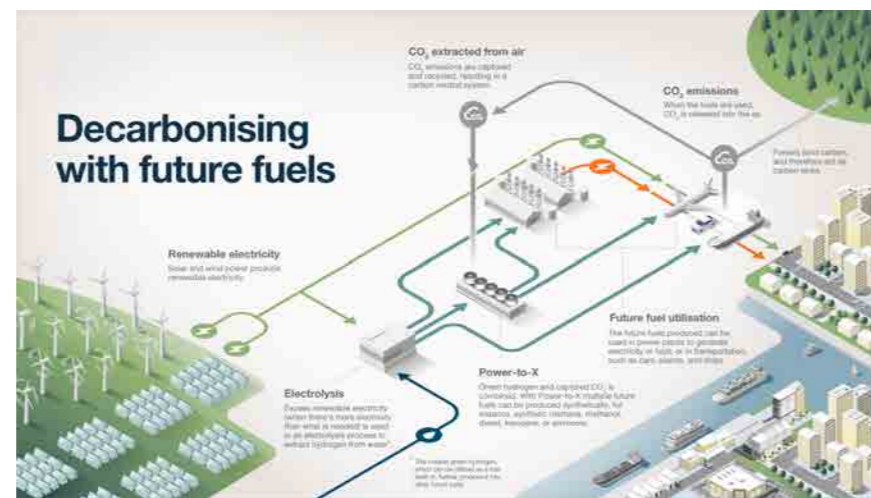
As renewable energy generation varies depending on the availability of wind, solar or other natural energy sources, it is necessary to have other dispatchable power sources that can be started and stopped quickly. This can be, for example, RICE generators. These are strong candidates for balancing power supply due to their fast start-up times and rapid load response, compared to other power sources. The heat generated can also be recovered for different CHP applications.

### System employed:

Multiple engine powered generators each with **1-20 MW** output.

### Decarbonisation pathways:

Engines are operated for less hours when the renewable share of the electricity mix increases, thereby decreasing system level GHG emissions. Fuels for the RICE generators can vary from using fossil derived fuels to low carbon and then renewable fuels, both gaseous and liquid. Most gas engines can be modified to transition to hydrogen fuel when hydrogen becomes available. Grid system optimisation and demand management may also be applicable.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Predictability of deployment	Pre-planned		Un-planned
Time on site	Extended		Short

### Example 3: Auxiliary generator for emergency use or backup use

#### Use description:

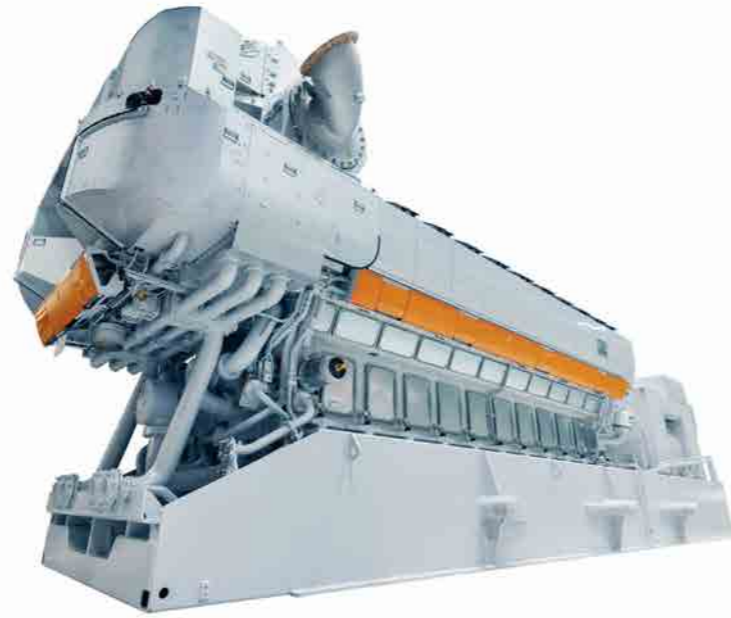
Backup generators for hospitals. The installed auxiliary generator, running on fuel stored on site, helps to maintain power in an emergency scenario. A highly energy-dense fuel is essential for safety and capacity. Local regulations may require emergency power plants to run for 7, 14 or 30 days.

#### System employed:

RICE powered electrical generator. Power output of engine unit will depend on the hospital size, typically **1-10 MW**.

#### Decarbonisation pathways:

Current diesel fuel use can be replaced with low carbon, moving to renewable liquid fuels. Drop-in fuels with high energy density are particularly suited to emergency plants.



#### Evaluation Criteria

#### Use Case Evaluation

Energy use	Low	<input type="range" value="60"/>	High
Work intensity	Low	<input type="range" value="60"/>	High
Type of use	Sporadic	<input type="range" value="20"/>	Continuous
Predictability of deployment	Pre-planned	<input type="range" value="80"/>	Un-planned
Time on site	Extended	<input type="range" value="20"/>	Short

## Example 4: Primary and backup power for data centre

### Use description:

Backup generators for data centres. Data centres are typically supplied by grid electricity, but they need a reliable backup solution in case of a grid failure. In this scenario, power is supplied by using the installed backup generators running on diesel or gas fuel. Gas engines are becoming more attractive, because they can run continuously as well as providing backup power at lower emissions.

### System employed:

RICE powered electrical generators. Power output will depend on the data centre size. Typically engine systems of **1–100+ MW** output used.

### Decarbonisation pathways:

Current diesel use can be replaced with renewable liquid fuels. Gas engines can also be modified to run on Hydrogen.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low		High
Work intensity	Low		High
Type of use	Sporadic		Continuous
Predictability of deployment	Pre-planned		Un-planned
Time on site	Extended		Short

## Example 5: Provision of heat and power for small village

### Use description:

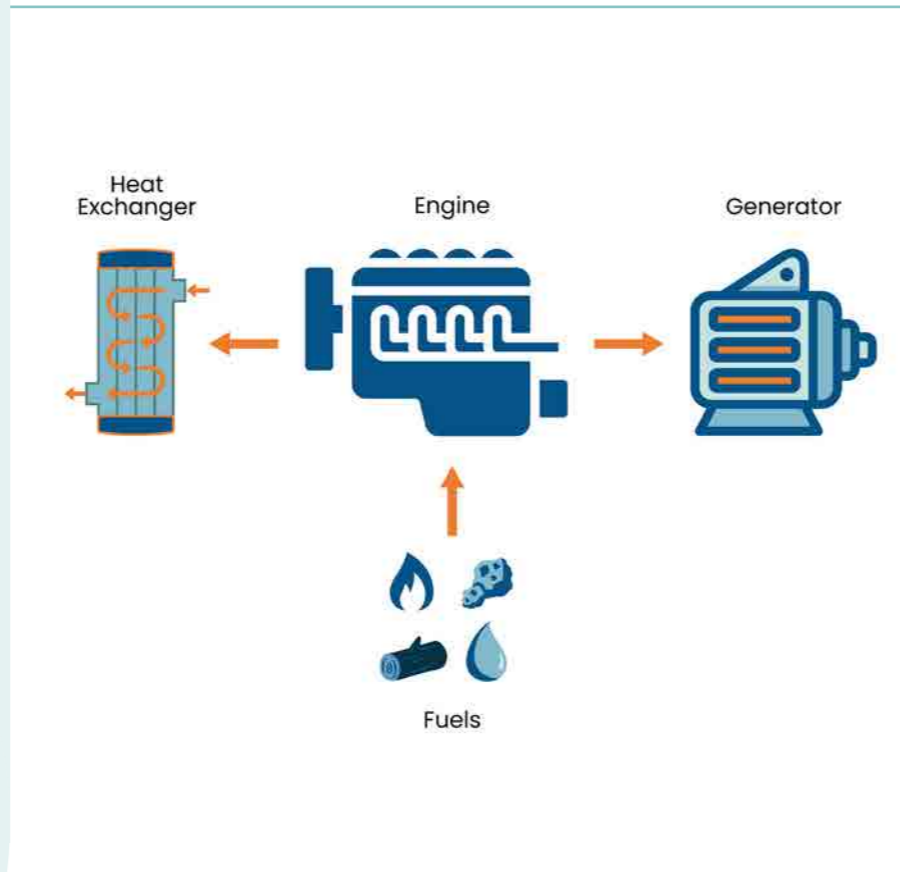
Provision of electricity and heat for a community or facility such as a village, office block or small factory.

### System employed:

RICE powered electrical generator of 1-10 MW with a similar amount of heat available. Fuelled by diesel or natural gas.

### Decarbonisation pathways:

Current diesel or natural gas use can be replaced with low carbon, moving to renewable, liquid or gaseous fuels.



### Evaluation Criteria

### Use Case Evaluation

Energy use	Low	<input type="range" value="75"/>	High
Work intensity	Low	<input type="range" value="75"/>	High
Type of use	Sporadic	<input type="range" value="50"/>	Continuous
Predictability of deployment	Pre-planned	<input type="range" value="25"/>	Un-planned
Time on site	Extended	<input type="range" value="10"/>	Short

## Conclusion

Stationary power plants are an important enabler of decarbonisation across society. Their primary purpose is to balance variable renewable generation with demand to ensure power availability and grid reliability. Where no electric grid or renewables are available, they are used as a prime power source. They are also essential as an emergency backup to maintain critical services such as keeping hospitals running when other power sources fail, for example when natural disasters destroy grid connections. Engines are one of the main solutions for data centre backup or continuous power supply, an emerging segment for liquid and gas fuelled engines. Fuel cell generation or battery storage can also be used in some circumstances.

Decarbonisation of these high-power, energy-efficient power plants can be achieved by using low carbon fuels before moving to renewable fuels. The engines in these power plants are adaptable to a wide range of fuels. The choice of fuels to decarbonise each installation will depend on its location and the local fuel options available.





03

# Appendix

## 1. Methodology

To help set out the decarbonisation pathways, EUROMOT convened industry working groups and conducted a comprehensive review, facilitated by a third party consultant, of the latest research and expert opinion on low and zero carbon solutions across Marine, Lawn, Forestry, Utilities, Rail, Non-Road Mobile Machinery, and Stationary applications (power plants).

EUROMOT also assembled industry working groups representing global powertrain manufacturers across all sectors to identify viable and practical new technologies and energy carriers across a range of working machines and power plants, use cases, and operating environments.

**Energy Carriers** are fuels and electricity (including batteries) containing stored energy that can be converted to other forms of energy which can then be used to power machines and power plants.

**Energy Converters** are the devices that convert energy from stored chemical energy (fuels) or electricity to mechanical energy – generally engines or motors (such as internal combustion engines, electric motors, hydrogen fuel cells combined with electric motors, hydraulic/pneumatic motors, and hybrid systems).

**Conversion Efficiency** is the energy out of a converter divided by the energy input. For example, the mechanical energy at the flywheel, divided by the stored energy available in the fuel used.

**Operational Efficiency** is a measure of the work a powertrain application can do compared to a theoretical maximum or to the incumbent powertrain's performance. For example, operational efficiency is reduced if a proposed powertrain reduces the payload of a goods carrying vehicle, or if the use time available is reduced by increased refuelling times.

## 2. Definitions

Some important definitions and principles must first be applied to enable a valid assessment of the technologies:

**GHG Emissions** CO<sub>2</sub> is the predominant Greenhouse Gas for this sector, but this also encompasses other GHGs such as nitrous oxide and methane, normally defined as CO<sub>2</sub> equivalent (CO<sub>2</sub>e) when using the GWP100 definition (the global warming potential of a specific greenhouse gas over 100 years).

**Life Cycle Analysis (LCA)** is a method of calculating the total CO<sub>2</sub>e emissions from a product, including other emissions such as nitrogen oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>), during its full lifecycle. That is throughout manufacture, use and disposal.

**Well to Wheel, (or Well to Wake for marine) (WtW), or Well to X (WtX)** emissions is the total (net) emissions generated when a fuel or energy carrier is created (such as when it is extracted from the ground or grown as a biological feedstock), when its energy has been converted in a machine and its end products emitted (e.g. CO<sub>2</sub> and water from burning a hydrocarbon fuel).



### 3. Powertrain Technologies Offering Pathways to Decarbonisation

#### a) Internal combustion engine

ICEs are today the most economical and versatile powertrains encompassing the widest array of industrial needs and environments. For over 100 years, ICEs have been almost the only form of industrial powertrains due to their ability to rapidly and efficiently convert readily available, energy-dense fuels into mechanical energy for a wide array of industrial needs and locations. Over a century of engineering evolution has produced highly safe, reliable, sustainable, compact, cost-effective, and efficient ICEs.

##### Efficiency

ICEs use readily available, energy-dense fuels that need limited storage space and can thus be easily and efficiently applied to any applications or operational use cases in any environment. They therefore give a high level of engine operational efficiency. ICE energy conversion efficiency varies depending on the application and can reach 55% conversion efficiency (the ratio of fuel energy inputs to mechanical energy outputs).

##### Emissions

Air quality emissions in ICEs have long been regulated and progressively reduced to minimal levels with, for example, the EU's 'Stage V emissions limits are >95%<sup>24</sup> lower than Stage I limits for NO<sub>x</sub> and PM (for 56 kW to 560 kW engines.)<sup>25</sup>

##### Security, availability, and affordability

Europe is a world leader in ICE technology with a mature domestic manufacturing base and supply chain. They do not use rare or strategically critical materials. This ensures a highly secure, accessible, and affordable supply of the powertrain parts and fuels essential to the operations of Europe's major industries and critical services. They face some supply chain vulnerabilities around materials needed for after-treatment such as platinum or palladium.

<sup>24</sup>EUROMOT (no date) Air Quality - Our strive for cleaner air

<sup>25</sup>International Council on Clean Transportation (ICCT), 2016. European Stage V non-road emission standards

\*In this paper we use the term internal combustion engine (ICE) to mean reciprocating internal combustion engines rather than all ICEs that might include e.g. turbine engines

#### b) Hydrogen fuel cells combined with batteries and electric motors

Fuel cells convert stored energy in fuels, usually hydrogen (although other energy carriers such as methane and ammonia can also be used), directly into electrical energy. Hydrogen is combined with oxygen to produce water, waste heat and electricity on a precious metal membrane. Fuel cell systems are reasonably compact and can have higher conversion energy efficiency than ICEs at light load.

Hydrogen fuel cells are a technology already in use in light-duty road vehicles yet remain unproven in industrial applications such as construction, agriculture and marine, where challenges remain around durability and performance degradation.

##### Efficiency

Fuel cells are more energy-efficient than ICEs at low loads where energy conversion efficiencies sometimes reach 60%.<sup>26 27</sup> At higher loads their efficiencies are similar to ICEs. Polymer electrolyte membrane fuel cells are more compact than battery electric systems and can be refuelled at similar speeds to ICEs. Yet, the lower volumetric energy density of hydrogen means hydrogen tanks need more onboard storage space or regular refuelling than ICEs running on liquid fuels, making the technology impractical for large machines and vessels with long operational hours. The fluids used in fuel cells (air, coolant and fuel) must be kept very pure and free from

contamination. Contamination will reduce the life of the fuel cell and may cause early failure. This is a particular challenge for many off-road applications such as agriculture or mining.

##### Emissions

Hydrogen fuel cells emit only water and warm air and produce no air quality or GHG emissions in use. The lifecycle carbon footprint of hydrogen fuel cells is however higher than (hydrogen) ICEs due to the need for precious and rare earth metals in the membrane, motor, and battery. The embedded carbon in fuel cells falls in the medium range between ICEs (low) and electric powertrains (high).

##### Security, availability, and affordability

There are risks around cost, scarcity, and strategic exposure of supplies due to the need for rare earth and precious metals from regions such as Africa<sup>28</sup> for some fuel cell components. There are significant projected shortages of some materials for fuel cells such as iridium.<sup>29</sup> Fuel cell manufacturing costs are currently much higher than for ICEs and similar or higher than for electric powertrains. However, fuel cells have more secure supply chains than battery electric systems as they require fewer precious or rare earth metals. Fuel cell systems for dynamic applications require a hybrid configuration with batteries.

<sup>26</sup>U.S. Department of Energy (no date) Hydrogen and Fuel Cells Technology Office: Fuel Cells

<sup>27</sup>Argonne National Laboratory, 2018. Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai.

<sup>28</sup>Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (2023) Study on the Critical Raw Materials for the EU 2023 - Final Report. Catalogue number: ET-07-23-116-EN-N, ISBN: 978-92-68-00414-2, DOI: 10.2873/725585

<sup>29</sup>McKinsey & Company (2024) Global Materials Perspective 2024

## c) Electric powertrains

**Electric powertrains convert electrical energy, either from a direct electricity supply or onboard batteries, into mechanical energy. They have the highest energy conversion efficiency of all powertrain technologies and produce no CO<sub>2</sub> or air quality emissions in use. Yet electric powertrains can have a higher lifecycle carbon footprint than other powertrain types due to the many raw materials needed for batteries and motors. Their industrial applications are limited by the lack of electricity distribution and charging networks in many non-road and industrial locations, slow charging speeds, and the need for very large batteries or regular recharging for high-powered machines.**

### Efficiency

Electric powertrain technology is the most energy-efficient powertrain, with a conversion efficiency of 75% to 90%. Yet, it is the least operationally efficient powertrain technology, as batteries have a far lower energy density than hydrocarbons or hydrogen and therefore need more frequent recharging or bigger batteries. Also, it needs to be noted that batteries need regular maintenance and recharging even in periods without use. That affects their feasibility for low-use applications like fire-fighting pumps, emergency backup or products for seasonal use such as recreational craft, farm equipment and harvesters. Off-board cables or catenary systems are only possible in limited scenarios and most industrial machinery would require onboard battery storage for freedom of movement. Off-board cables or catenary systems are possible in limited use cases for direct power or on-the-move recharging, however most industrial machinery would require onboard battery storage for freedom of movement.

Refuelling times are slower than hydrogen or liquid fuels, and high-powered electric grid and fast charging infrastructure is unavailable in many locations. This limits the feasibility of electric powertrain technologies for high-powered machines with long operating hours in off-grid locations and rules out its use in many sectors, for example, oceangoing marine or harvesting.

### Emissions

Electric power and propulsion systems produce no air quality or GHG emissions in use. However, electric powertrains can have a high lifecycle carbon footprint compared to other technologies due to higher production-phase<sup>30</sup> and end-of-life emissions from batteries.<sup>31</sup>

### Security, availability, and affordability

Battery electric technologies face significant supply chain bottlenecks due to their reliance on raw materials from outside the EU such as critical minerals concentrated in Asia. For example, demand is projected to exceed the supply of dysprosium for permanent magnet motors<sup>32</sup> and of lithium for lithium-ion batteries.<sup>33</sup> The high cost of battery materials also makes electric powertrain technologies less economical than ICEs. The EU Carbon Border Adjustment Mechanism (CBAM) could further increase these costs and shortages due to the high production phase emissions associated with many key metal ingredients.

<sup>30</sup>European Union (2022) Towards a sustainable, circular, European battery supply chain

<sup>31</sup>International Energy Agency (IEA), 2024. New IEA online tool compares lifecycle emissions from traditional and electric cars.

<sup>32</sup>McKinsey & Company (2023) The net zero materials transition: Implications for global supply chains

<sup>33</sup>McKinsey (2024) Global Energy Perspective 2023: Transition bottlenecks and unlocks

## 4. Energy Carriers Offering Pathways to Net Zero

### Reduced carbon fuels

**Moving from liquid to gaseous fossil fuels offers an important first step towards decarbonising hard-to-abate sectors from seagoing marine to stationary power generation. These widely available, affordable fuels that require modification to liquid fuel fired engines could accelerate decarbonisation of the existing global fleet of internal combustion powered machines and power plants, where conversion is practical.**

### Energy density and ease of adoption

Natural gas and petroleum gas have high gravimetric energy density, and volumetric density can be maximised by liquefaction or storage under pressure. This means that they can be accommodated in most applications in place of liquid fuels. Refuelling frequency and refill times are similar to diesel or gasoline, and they can thus be easily integrated into existing operations.

### Handling requirements

Both gases must be compressed and stored at high pressures, or as liquids to reduce storage space.

### Emissions and net zero potential

LPG/DME and natural gas can deliver respectively a 10–20% reduction in carbon emissions compared to diesel and gasoline. Methane slip needs to be controlled to ensure GHG reductions. Air quality emissions are similar or lower than diesel and can be reduced to extremely low levels using available engine technologies.



## Low Carbon and Renewable Fuels

### Alcohol fuels (ethanol, methanol)

As neat fuels they are mostly used in Spark Ignited engines as replacements for gasoline, while also used in larger dual fuel Diesel engines. They can be of biological origin or produced synthetically.

#### Energy density and ease of adoption

Alcohol fuels have a high energy density but around 50–60% lower than petrol or diesel so they will require more regular refuelling or increased tank capacity.

#### Handling requirements

Alcohol fuels must be treated with similar caution to petrol or diesel. Methanol is a skin irritant and can be toxic to humans if consumed while ethanol can also cause irritation of the eyes, skin and respiratory tract.

#### Emissions and net zero potential

Emissions and net zero potential GHG emissions at the tailpipe are approximately 8% lower<sup>34</sup> for methanol than fossil diesel/gas oil. WtW GHG emissions can be substantially lower depending on the manufacturing process. Air quality emissions are similar or lower than fossil diesel or gasoline and can be reduced to extremely low levels using available engine technologies. Other pollutants such as formaldehyde need to be controlled.

### Biomethane

Biomethane is a purified form of biogas that offers a sustainable alternative to fossil gas<sup>35</sup> and can be used in a fuel blend or as a drop-in renewable replacement fuel for natural gas. It could be substituted for natural gas without any change in transmission or distribution infrastructure.<sup>36</sup> It can be made from organic waste, and thus also forms a key part of waste management.

#### Energy density/ease of adoption

Biomethane is highly energy-dense and storable and is a drop-in replacement fuel for fossil gas.

#### Handling requirements

Biomethane has the same properties and handling requirements as natural gas.

#### Emissions and net zero potential

Biomethane can be net zero GHG emissions if made from biomass waste or energy crops and sustainably processed and transported. It can even be carbon-negative if made from animal manure. Air quality emissions are lower than diesel.

<sup>34</sup>International Maritime Organization (2022) 2022 guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships

<sup>35</sup>European Union (2022) Biomethane

<sup>36</sup>IEA (2020) Outlook for biogas and biomethane: Prospects for organic growth. World Energy Outlook special report. Licence CC BY 4.0

### Biogasoline, biodiesel, HVO

Liquid and gaseous biofuels and biomass fuels can be drop-in replacement fuels when blended with their fossil fuel equivalents. HVO is a drop-in replacement for diesel. These drop-in fuels can be rolled out with already existing energy distribution infrastructure, offering an opportunity to rapidly decarbonise the current and future machine fleet.

#### Energy density/ease of adoption

Biogasoline, HVO and biodiesel are highly energy-dense, and can be refilled as quickly and frequently as conventional fuels and with similar storage requirements. HVO is a drop-in fuel.

#### Handling requirements

Biogasoline, biodiesel and HVO have similar handling requirements to traditional diesel and gasoline.

#### Emissions and net zero potential

Biofuels can deliver up to a 100%<sup>37</sup> reduction in GHG emissions if produced using sustainable methods from biomass wastes and residues or purpose-grown energy crops and with sustainable methods of processing and transportation. They capture CO<sub>2</sub> emissions through photosynthesis. Air quality emissions are similar to, or lower than diesel, and can be reduced to extremely low levels using available engine technologies.

<sup>37</sup>Brown, C. and Tao, L., 2023. Biofuel Production and Greenhouse Gas Reduction Potential. National Renewable Energy Laboratory.

### E-Fuels (e-Methane, e-Methanol, e-Gasoline, e-Diesel)

E-Fuels are synthetic fuels, resulting from the synthesis of renewable hydrogen produced by the electrolysis of water, using renewable electricity and CO<sub>2</sub> captured either from a concentrated source (flue gases from an industrial site or biogas plants) or from the air (Direct Air Capture). They are drop-in replacement fuels compatible with existing engines and thus offering potential pathways to full decarbonisation for all ICE-powered working machines and power plants.

#### Energy density/ease of adoption

E-Fuels are as energy-dense as their fossil equivalents and thus do not need more storage space or more frequent refuelling.

#### Handling requirements

E-Fuels can be handled with the same care as conventional fuels to prevent ignition, spillage, and evaporation.

#### Emissions and net zero potential

E-Fuels are the most energy-intensive fuels to produce. They are net zero CO<sub>2</sub> emissions when they are made using CO<sub>2</sub> captured from other sources and mixed with green hydrogen. They are classed (in the EU) as Renewable Fuels of Non-Biological Origin (RFNBOs) with GHG reduction greater than 70%.

## Low Carbon and Renewable Electricity

Renewable electricity is produced from energy sources that are naturally replenished as they are used. These are: wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas as outlined in the Renewable Energy Directive (RED). Low carbon electricity is produced from energy sources that produce significantly less GHGs (CO<sub>2</sub>) when compared to fossil fuels. They are not renewable. Examples are: hydrogen produced from electrolysis without using renewable electricity, hydrogen from natural gas with carbon capture, low carbon hydrogen-derived synthetic fuels, nuclear.

### Energy density/ease of adoption

Electricity must be used as it is generated or stored in batteries. When stored in batteries, its volumetric and gravimetric energy density is low. This makes it impractical for some applications and use cases.

### Handling requirements

Special measures may be needed when using electricity over 60 volts.

### Emissions and net zero potential

Decarbonisation can be achieved during the generation process by using renewable energy sources. GHGs are not produced at the point of use.

### Emissions and net zero potential

Electricity produces no air quality emissions at the point of use, but they may be produced during generation. See second sheet on energy carriers table

## Renewable hydrogen

Renewable hydrogen is a renewable fuel made by electrolysis of water using renewable electricity. However, there are other ways of producing hydrogen. Hydrogen produced by other means may be a significant contributor during the transition period.

### Energy density/ease of adoption

Renewable hydrogen has medium energy density when stored at high pressure or liquefied and has similar refill times to liquid fuels. Hydrogen gas tanks need about eight times the storage space and liquid hydrogen tanks four times the space of a diesel tank<sup>38</sup> for an equivalent amount of energy. The need for a substantial increase in onboard volume and mass or significantly reduced range<sup>39</sup> makes hydrogen impractical for some sectors.

### Handling requirements

Hydrogen must also be stored at very high pressures or low temperatures and requires special safeguards against ignition or contamination, increasing the cost and complexity of distribution and storage. For marine seagoing engines, work is ongoing on guidelines for the safe use of hydrogen as a marine fuel.

### Emissions and net zero potential

Synthetic hydrogen is produced from electrolysis and is zero GHG emissions when produced with renewable electricity.

## Renewable ammonia

Renewable ammonia is a renewable fuel that will be central to decarbonising hard-to-abate sectors such as seagoing marine.

### Energy density/ease of adoption

Renewable ammonia has medium-to high-energy density and requires around three times the storage volume of a diesel tank for the same amount of energy.<sup>40</sup>

### Handling requirements

Ammonia gas must be stored at high pressures or liquefied and is also highly reactive, which may restrict its use in sectors such as agriculture or construction. Care is needed to ensure ammonia does not cause cracks in steel pressure vessels. For marine seagoing engines, work is ongoing on guidelines for the safe use of ammonia as a marine fuel.

### Emissions and net zero potential

Ammonia can have net zero CO<sub>2</sub> emissions when produced from renewable electricity and renewable hydrogen. Possible emissions of N<sub>2</sub>O would need to be controlled to reach net zero GHG emissions.

<sup>38</sup>CECE (2021) Position Paper. The role of construction equipment in decarbonising Europe

<sup>39</sup>ICOMIA (2024) Pathways to Propulsion Decarbonisation for the Recreational Marine Industry Synopsis

<sup>40</sup>CECE (2021) The role of construction equipment in decarbonising Europe

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