Electric Ferries in the Baltic Sea Region Compendium

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Impressum

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Acknowledgement

We would like to thank all contributors, associated partners and project partners as well as colleagues for their willingness, support and the helpful exchange of experiences during the joint work on the project and on this compendium.

We thank for the joint transnational cooperation with the partners of the project "BSR electric" and especially the lead partner, HAW Hamburg, for its supporting organizational work.
Above all, we would like to express our gratitude for the fact that the Interreg project gave us the opportunity and the possibility to work on this extensive topic of water-bound electric mobility.

Foreword/Summary

The present compendium was developed within the joint Interreg project "BSR electric", which focused on the various solutions and applications of electromobility and their use in urban areas and transport systems. In the "Electric Ferries" application case, experiences and research were gathered, analyses and comparisons were made and an attempt was made to summarise these in a handbook. The processing period was advantageous in that at the beginning of the project only a few examples of electric ferries in the Baltic Sea region were known. The number and awareness of successful examples increased the awareness of those involved, such as municipalities, public transport companies and operators, of the usefulness and feasibility of the project.

The increasing stakeholder involvement in electrification, experiences on study trips, feedback in workshops, exchange of experiences and information events showed a need for information and exchange of experiences on the part of stakeholders. The compendium is thus an attempt to meet this need.

Essential for the implementation of electric mobility solutions is the knowledge of the technical-physical interrelationships and boundary conditions, in particular the electrical energy supply, as well as shipbuilding and infrastructural topics. The complexity of these topics has concrete implications for the procurement, construction, maintenance and operation of electric ferries. In addition to technical questions, the compendium attempts a socio-economic and historical classification of mobility and electric mobility.

Electric ferries with batteries as the energy source and urban operating and driving profile can be easily reconciled with the technical, energy and economic framework conditions. Urban electric ferries can be regarded as good examples of electric mobility on water. There are also successful examples of larger electric ferries operating in coastal waters, although the battery as an energy source poses demanding challenges for the energy supply and charging infrastructure depending on the location of use. For this reason and due to the increasing use of renewable energy sources, the supply of electrical energy based on hydrogen and fuel cells or alternative fuels is becoming increasingly important in this power class.

For clean shipping with large ocean-going vessels with propulsion powers of several tens of megawatts, the use of low-sulphur fuels in classic diesel propulsion systems will remain predominant for the time being. Electric drives as a contribution to clean shipping in this power class are limited to special ships in the research and military sector, which generate the required electrical energy e.g. by means of nuclear-powered generator sets. The recently emerging and currently discussed possibility of energy supply by means of wireless transmission of electrical energy over any distance and power [1] is not discussed here. This possibility is not yet commercially available to most stakeholders and is also not relevant for the operation of urban electric ferries. If necessary, this topic can be deepened in future work.

Contents

1 Introduction

„ Most of the change that has so far taken place in human history has been gradual – with the great "revolutions" being mere punctuation marks to a slow, eludible process. In contrast, the approaching transformation will come more rapidly and will have deeper consequences for the way and even perhaps for the meaning of human life than anything experienced by the generations that preceded us.
America is already beginning to experience these changes and in the course of so doing it is becoming a "technetronic" society: a society that is shaped culturally, psychologically, socially, and economically by the impact of technology and electronics, particularly computers and communications. The industrial process no longer is the principal determinant of social change, altering the mores, the social structure and the values of society. This change is separating America from the rest of the world, prompting a further fragmentation among an increasingly differentiated mankind, and imposing upon America a special obligation to ease the pains of the resulting confrontation." [2], [3]

Fundamental changes in mobility, the energy sector and industry have taken place over the last decade. Existing centralized structures, mainly based on fossil fuels, are apparently being challenged both by politicians and by industry itself. Energy companies, primarily in the oil industry, are increasingly turning to renewable energy sources, agriculture, alternative fuels and are aggressively promoting CO2 and energy saving measures. Automobile companies that have hesitated for a long time are present on the market with electric vehicles and are reducing the CO2 emissions of their fleets.

Users and consumers, especially the younger generations, have grown up with a new paradigm, shaped by the Club of Rome report [4] published against the background of a growing world population and dwindling resources. As Brzezinski writes, raising and changing awareness of the sustainable use of environmental resources and energy has spread worldwide as a gradual process in all areas of societies and populations and indirectly influences these developments. Since the report was published, the world population has almost doubled. (1976: 4,061,399 and 2020: 7,758,157) [5]. Based on current assumptions, it is estimated that with continuing population growth, advancing industrialisation and globalisation, energy demand can no longer be met in the long term on the basis of mineral oil and fossil resources. Therefore, a change in the current energy policy or a departure from it is seen as necessary. This provides a basis for strategies to electrify broad areas of economic and social life.

Ways and trends that roughly outline this change are

- Urbanization and electric mobility,
- Technetronic change: Digitization, Informationalisation,
- Use of renewable energy sources,
- Industrial change,
- Education and social change.

Every trend can be broken down into its diversity, into all areas of life, from science to business, from medicine to mechatronics.

"The future of mobility is electric." (anonymous)

Mobility improves the quality of life and enables economic and social participation.

Against the background of increasing urbanization, demographic and social change and changes in habits, new concepts are also needed for mobility and mobility services. Electric mobility is gaining ground in many areas of daily passenger and freight traffic. The number of registered electric vehicles is rising continuously from year to year. Currently, at the beginning of 2020, around 7.9 million electric cars are registered worldwide. This represents an increase of 2.3 million vehicles compared to the previous year. [6]

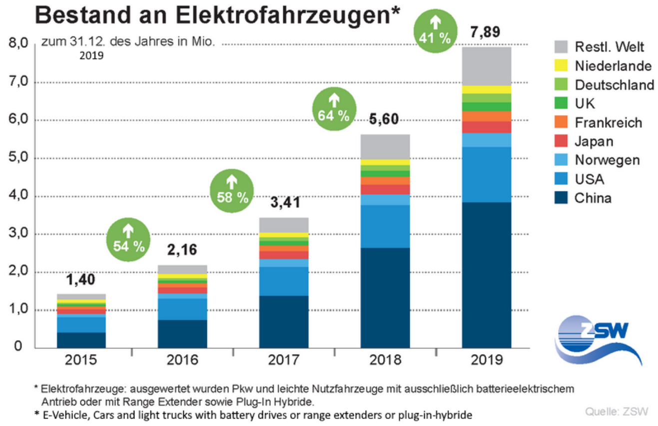


Figure 1 Electric vehicles: Inventory and increase of electric cars. [6]

Electromobility is a multifaceted concept but not a new one. What is new is its scope and networking, both in the technetronic sense with its effects and on social processes.

We are currently at the beginning of a process of networking that encompasses all facets of mobility and electrification (energetics). From traditional electric means of transport to individual small vehicles and finally to autonomous driving, information networking is taking hold.

Physical mobility" and information about mobility are merging together and electric mobility is a driver of this increasing "informationalisation". As “mobile computer platforms”, electric vehicles not only take over the control and steering functions required for the technical operation of the electric vehicle, but involves the user of the vehicle in that control also. This trend is finding its first highlights in highly automated and autonomous driving.

Effects of networking and informationalisation are recognizable as urban usage trends in the form of multimodal virtual transport networks that combine a wide range of transport modes in a user-oriented way. These combinations (navigation and routing solutions, car-sharing, sharing systems, individual small electric vehicles, classic multimodal public transport, etc.)

create new opportunities for urban business models. Electromobility is most clearly and strongly experienced individually in the field of passenger transport and especially through individual mobility with its various manifestations. Individual electromobility is a field of experimentation for own experiences and new business models. In principle, the networking of information and mobility enables resources to be used optimally, traffic and city centers to be relieved, the environment to be protected and social participation to be implemented more efficiently.

Electromobility therefore means a strong mutual influence of technical, demographic and social interactions, which are currently perceived primarily as an urban phenomenon. Via the interface of information networking, an expansion to existing classic means of transport such as ferries, trains, buses, etc. is taking place, which in turn will become part of electromobility.

As a conclusion to the question to be examined, whether electric ferries and electric water taxis can make a meaningful contribution to urban mobility, the answer can be given with clear conviction as 'yes'.

Electric ferries are characterized by their light and robust construction and design. They offer safe and reliable operation, produce no local emissions and are quiet. With a slightly higher investment for the vehicle and the infrastructure, they are economical, efficient and, depending on the technical equipment, can generate part of the required energy themselves (solar energy).

It is in the nature of a ferry that the vehicle always travels on the same line. It commutes from "socket to socket" or, in technical terms, a ferry has a fixed driving profile. Examples in the Baltic Sea region show that in principle a significant proportion of existing ferry lines with short distances, on inland waterways and protected coastal waters can be navigated by electric ferries. This applies to passenger ferries and car ferries, but passenger ships can also be operated entirely by electric propulsion.

Nevertheless, the handling and implementation of electric mobility requires a minimum of basic knowledge on the part of the community and the transport company. Municipalities, regional planners, transport companies and other stakeholders are faced with a multitude of questions and it is advisable to involve experts and talk to people with experience. This compendium is an attempt to provide an introduction, explain the technical background and give an overview of the topic of electro-mobility on water by using examples.

2 Electric ferries in the BSR

2.1 Motivation

The motivation for the project "BSR electric - Fostering of e-mobility solutions in urban areas in the Baltic Sea Region" resulted from the focus on electric mobility solutions for diversified urban transport tasks. The idea for the project was born at a time of increasing activity to introduce electric mobility solutions. The project should investigate, describe and demonstrate potentials of different possibilities of electro-mobile applications and thus make an additional contribution to the integration into the social use.

The project partners from cities and institutions in the Baltic Sea region contributed their proposals to the project according to their specific needs and preferences. These focused on the implementation of solutions for electrified urban logistics with e-vans, the integration of e-scooter and electric bike systems for commuters, the introduction of e-buses and the implementation of urban electric ferries.

Target groups of the project and its results are stakeholders of the public sector, administration and authorities as well as companies, such as public transport companies, hospitals, housing companies, shipping companies and others.

The project has been implemented within the framework of the Baltic Sea Region 2014-2020 Interreg BSR Program, which promotes integrated territorial development and cooperation for a more innovative, accessible and sustainable Baltic Sea Region. Partners from countries around the Baltic Sea work in transnational projects on common key challenges and opportunities.

The project partner ATI Küste GmbH - Gesellschaft für Technologie und Innovation - has, in addition to the joint activities of the project partners, focused on the application case "electric mobility on water" and in particular on the question of how electric ferries and electric water taxis can be a useful part of urban transport systems.

2.2 Background

Since the beginning of the 2000s, ATI Küste GmbH has been active in the following fields: renewable energy, maritime technology, hydrogen technology, fuel cell technology, and electromobility as well as technical innovations for companies. Electric drives, maritime systems, lightweight construction, energy converters, alternative fuels as well as traffic systems and concepts were and are topics in which the ATI Küste GmbH offers expertise and consulting. For this purpose, ATI Küste GmbH has specific knowledge, experience and competences which are regularly provided for stakeholders, companies and administrations in consultations, projects, workshops and conferences. Some examples.

- "VEM - Joint project Increasing efficiency in marine technology", Use of fuel cells in underwater systems, joint project, State of Mecklenburg-Vorpommern, BMWi (until 2010);
- "INPROMAR - Innovative Propulsion Systems for Manoeuvring Maritime Systems", Rim Propeller System, ZIM Network, BMWi (until 2012);
- "MARIMO - Development project for maritime electromobility", topics: Antifouling, propulsion, energy supply, lightweight construction and others, studies and other activities, internal project of ATI Coast, (from 2013);
- INNOGEO - Interdisciplinary Network for the Promotion of Innovations in the Geoinformation Industry, Innovation Forum, BMBF (2018);

- "E-Boot 4.0 - Electric Boats for Leisure and Application of Industry 4.0 Principles in Boatbuilding", fuel cell and battery systems, networking and remote maintenance; ZIM network, BMWi (since 2018);
- "Methacycle - Methanol cycle for storing renewable energies, joint project, specialist programme of the Federal Ministry of Education and Research (until 2019).

Due to its long-standing activities, the ATI Küste is networked and jointly active through various contacts to local authorities and administrations, transport companies, shipyards and manufacturers as well as to scientific institutions, universities and stakeholders.

The concrete reason and motivation for this project task was the implementation of an electric ferry as a replacement for a diesel-powered vehicle for an urban ferry connection. Due to its expertise, ATI Küste GmbH has been accompanying the developments and activities for the electrification of urban ferry lines for a long time.

2.3 Challenges and issues

The application case "urban electric ferries" investigates the question of the usefulness of electrically operated ferries and water vehicles in public transport systems. Free-moving ferries are a necessary and traditional means of public transport, especially in coastal and port cities, in cities with large bodies of water and on rivers without sufficient current. For the project as a whole as well as for the handling of the application case, the following questions were relevant for stakeholders:

Which results for better mobility in cities does the project deliver?

The changeover to electric ferries and electric passenger ships requires substantial investments both in vehicles and infrastructure as well as in the energy supply of the ships. For municipal households, investments of this magnitude are always a great challenge and rarity. The necessary knowledge must be acquired for the one-off or rare case and the experience gained is often lost again.

Nevertheless, the transition to electromobility is a trend, because there is a demand in the municipalities for the improvement of the urban environment and for improvements in the networking of multimodal urban transport systems, which require cooperation between different stake-holders at local, regional and transnational level. Supporting the implementation of electric mobility on water in all its complexity, by providing knowledge, exchange of experience and trust for cooperation of stakeholders should be one result of the project.

What are the challenges facing city administrations and transport companies?

The challenge for free-moving electric ferries is that the necessary electric energy for safe passage must be carried on board. In free travel, the ship, propulsion and on-board operation, operates as an autonomous system. Electrical energy, as electrical "current" is by definition something dynamic and cannot be stored directly but can only be converted "indirectly" from other forms of energy, usually chemical ones. The question here is, how much energy can be stored and converted on board? How large is the radius of action? What costs and investments are required?

The challenges in the procurement and implementation of electric ferries thus consist in the exact determination of the ship's requirements, its concrete purpose, such as the route, number of revolutions, travel and lay times. In addition, the external conditions, the sailing area, the traffic geography, meteorological and climatic conditions must be taken into account. Especially the winter climatic conditions in large parts of the Baltic Sea region pose great challenges for the battery equipment and the charging infrastructure.

For the technical implementation of the ship, in particular the energy supply system, it is necessary to precisely determine the ship's sailing profiles under the given technological conditions. This results in the designs for power, propulsion energy, energy supply system, charging infrastructure etc. Ship and port (jetty) always form a unit, especially in the case of ferries.

Due to the relative novelty of the technology, technical and economic risks are still very closely linked. The prices and lifetimes of essential components are currently still high and this leads to certain uncertainties in the decision-making process for the investment and operation of electric ferries.

How can city administrations benefit, and which cities can?

Benefits for city governments are intangible, i.e. a modern electric ferry improves the image of the city, brings political prestige among its citizens and other cities. Its implementation is a contribution to the improvement and preservation of the urban environment and helps the city to achieve long-term and international goals. In principle, all cities and communities that operate ferries in their public transport system will benefit from it in the long term.

The operation of the ferry from the perspective of the city is generally implemented by awarding concessions to operators. Here the city benefits from the higher reliability and reduced downtimes of modern electric ferries for the realisation of public transport.

How do citizens benefit from the project results?

Citizens benefit directly and indirectly from the modernisation of a ferry connection. Electric ferries are major investments for a city, which have to be well prepared, planned and tendered. Compared to conventional ferries, however, electric ferries have many advantages. They offer improved environmental protection, comfort and opportunities to save fossil energy sources. Modern electric ferries offer comfort due to emission-free and silent operation, which will be shown by higher satisfaction in daily use and citizens' pride in the city's innovation.

Why is a transnational cooperation project necessary for this?

The topic of urban electric ferries is of great interest not only locally. Due to the traditional partnerships of the Baltic Sea countries, there is cooperation between the municipalities and Baltic Sea cities. When searching for and trying out suitable solutions and their implementation as well as exchanging experiences, stakeholders can benefit from each other transnationally and improve the quality of life of their inhabitants and guests. This is an essential aspect in this complex technical and social task, which can be solved most effectively in transnational cooperation.

The realisation of an electric ferry in a municipality makes a concrete contribution to achieving the environmental and climate targets set. In addition to electric buses and electric municipal vehicles, electric ferries are a good example of how electric mobility can be implemented professionally and quickly for society. Due to the comparability of requirements for other regions and cities in the Baltic Sea region, it has transnational relevance.

In addition, electric ferries offer attractive tourist opportunities with a good external impact for the cities. In contrast, diesel-powered ferries and passenger ships, due to technology, produce exhaust fumes, noise and other emissions that affect comfort and have a negative impact on the urban environment.

2.4 Implementation, methods and outputs

2.4.1 Capacity building

An essential part of Interreg projects and thus also of the "BSR electric" are trans-national cooperation and so-called capacity building measures. Capacity building includes the transfer and dissemination of expert knowledge, results and recommendations for stakeholders, which are developed within the project. Formats used for this are workshops, conferences, but also digital methods such as webinars and online conferences. Especially in the last year of the project, 2020, these online formats were used more intensively for dissemination and for bilateral and multilateral communication.

2.4.2 Obtaining information

Research, interviews and study trips were undertaken to develop the content. Further sources of information were visits to operators of electric ferries in service. Study trips were made to Finferrie's electric ferry "Elektra" (Parainen to Nauvo in the Turku Archipelago), to Norled's "Ampere" in the Sogne Fjord between Lavik and Oppedal, to "Future of the Fjords" in the Sogne Fjord and to "Weiße Flotte" with their "Fährbären" in Berlin and in the shipyard of Oranienburg. Further sources of information were research in the available sources (literature and internet) and translations of various materials.

The focus on these methods was chosen in particular because at the beginning of the project, the project partners were faced with the question of how to implement a pilot phase specifically for the application "electric ferries". Due to the high investment costs, a pilot project was impossible and therefore the focus was on collecting best practice examples, experiences, developing material for knowledge transfer and recommendations for stakeholders using the methods mentioned above.

The fact that in the course of the project regional as well as international procurement processes for electric ferries were started, has proven to be advantageous. This gave the opportunity to follow the procurement process with the tender and to evaluate the experiences made.

2.4.3 Actions

The aim of the project work and implementation under the conditions described above was to contribute knowledge and skills to the project and also to take advantage of the opportunities to acquire new specialist knowledge, to deepen it further and to make it available to stakeholders in a form that is beneficial to them.

These measures and initiatives were closely linked to the core topics of electromobility, established references to related topics and developed and strengthened the cooperation and partnership. Methods and actions for the implementation of the project were analyses of the state of the art and knowledge transfer through webinars, workshops and conferences.

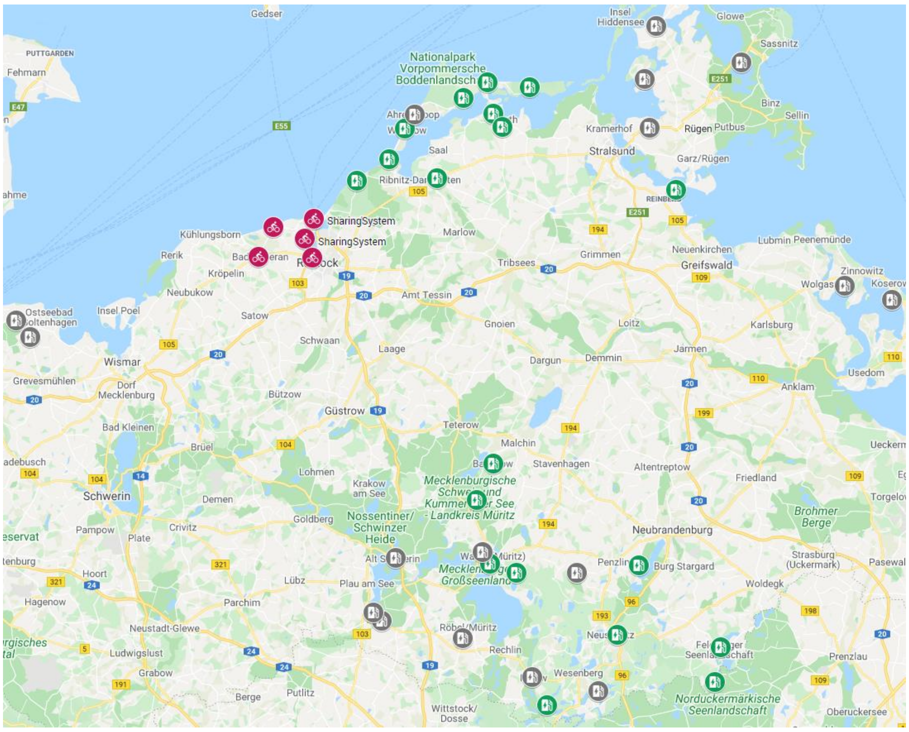


Figure 2 Mapping of charging stations for bicycle and water tours as well as possible ferry stations in Mecklenburg-Vorpommern. [7]

As mentioned, it was clear that a pilot could not be realized. Therefore, on the basis of selected examples and applications of electric ferries and electric ships in the Baltic Sea region, an attempt was made to draw conclusions. Examples were identified and analysed, technical data and information for decision makers were compiled and charts were produced. The research, analyses and summaries have addressed these issues, among others.

- Existing electric ferries as best practice examples in the Baltic Sea region,
- potentials for electrification of ferry lines in the Baltic Sea region,
- analysis of concepts, studies and documents for the realisation of electric ferry projects,
- analysis of technical systems for electric mobility on the water,
- manufacturers of electric ferries and their components,
- alternative fuels, hydrogen, fuel cells and battery systems as well as hybrid systems for electric shipping,
- shipbuilding issues for electric navigation,
- design of energy supply systems,
- automation and autonomous systems, digitalisation for water vehicles, such as electric ferries,
- operation and maintenance of electric ferries,
- training of skippers and maintenance personnel.

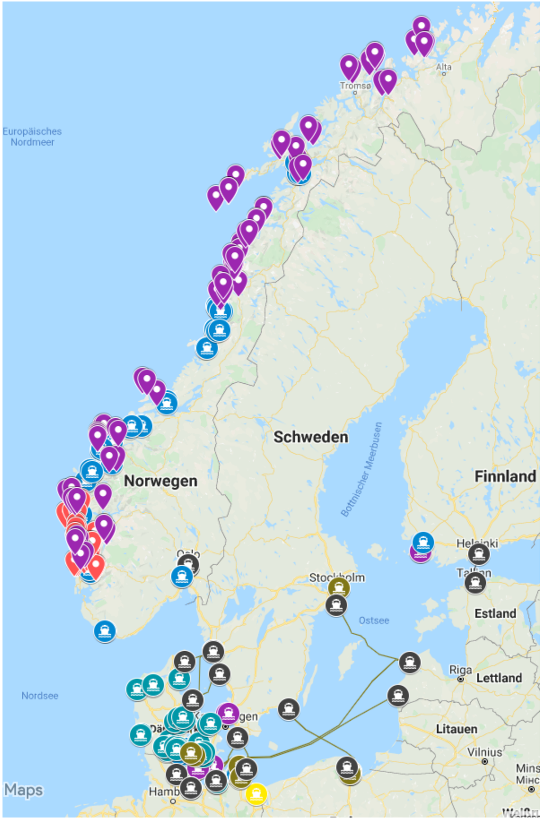


Figure 3 Mapping of potentials for electric ferries in the Baltic Sea Region. [7]

Figure 4 Mapping of potentials for electric ferries in Northern Germany. [7]

In addition to these aspects, fundamental socio-economic questions of public transport systems against a historical background of industrialisation, urban development, settlement policy and urbanisation and their demographic consequences also played a role.

2.4.4 Roadmap and Compendium

In addition to the main use case, the implementation consisted of working and interacting with the project partners to jointly work on the other use cases and the common roadmap.

Based on the experience gained in previous and ongoing projects, the "BSR electric" project made use of the opportunities to further deepen specialist knowledge and to support stakeholders as a qualified consultant in their decision-making. In addition to active participation in regional conferences with regional administrations, scientific institutions, chambers of industry and commerce and politics, e.g. through presentations or workshops, the following were examples

- Consultations for the preparation and participation in the tendering procedure as well as preparation of the kick-off event for the establishment of the hydrogen region of the district of Rostock;
- Consultations, support and preparation for participation in the tender Smart Cities for the Hanseatic City of Stralsund, in particular for participation in a tender for an autonomous shuttle as a feeder to relieve the inner-city traffic "OLLI - Challenge" of the company Local Motors;
- Joint development of a concept and participation in the tender for a seed-money project (Interreg BSR) on the subject of "HeatSmart - Alternative Energies for Heat Supply" with partners from Estonia, Russia, Finland and Germany;

- Participation in the project platform "CSHIPP - Clean Shipping Project Platform", in which ATI Coast as a partner represents the project "BSR electric" and introduces the topic of electric ferries as a useful option for clean shipping Experiences made with smaller urban electric ferries can be used with restrictions and adjustments as a basis for implementation for larger ships and special ships.

The output of the project, especially of the application "electric ferries", was planned as recommendations and working aid with checklists, explanations and evaluations for stakeholders in form of a white paper. This output serves the purpose of facilitating the planning and implementation of environmentally friendly electric mobility, especially urban electric ferries, for decision makers and stakeholders in municipalities and companies. As a compendium, it is intended to provide an overview of technical details and interrelationships, generalised experience and a decision-making aid for cities and municipalities in the Baltic Sea region in the planning and implementation of electric ferries for urban transport systems.

3 Urban Electric Ferries - Use Case 7

The application case "Electric Ferries for Urban Transport Systems" examines the question of which technical systems are required, which technical and economic risks have to be considered and how useful electrically operated ferries and water vehicles can be in public transport systems.

Spontaneously, the question of the usefulness of electric mobility can be answered with "yes". A second look at the subject matter requires more in-depth consideration, which has to do with the novelty of the topic, especially when it comes to freely running electric ferries. In contrast to electric cable ferries across rivers, the challenges for technical systems, prices and costs of procurement, operation, maintenance and legal issues are fundamentally different.

3.1 Ferries and possibilities of electrification

A ferry is by definition a means of transport by which passengers or goods are transferred across a waterway. The word ferry is derived from the Middle High German "vere", and Old High German "ferian" and means "to travel by ship". [8]

In urban transport networks, ferries are used where rivers, waterways, lakes and other bodies of water have to be crossed within city traffic. Ferries are characterised by the fact that they regularly travel the same route. Distinguishing features of ferries include Ship handling, type of drive, energy supply, speed, construction, navigable waters (high seas and inland waters).

In principle, electric drives are possible in all types of ferries. The current technical possibilities of electric power supply determine the feasibility and economic efficiency. Free-moving ferries must have a self-sufficient energy supply for propulsion and on-board operation. The energy stored on board must be sufficient for safe passage. For urban ferries, electrification makes particular sense because smaller ships and their travel profiles with short distances and travel times require low propulsion power. The use case of the project focuses on this type of electric ferries.

3.2 Types of ferries

3.2.1 Non-free moving ferries driven by the current of the water

Yaw cable ferries use the current of a river for propulsion. The ferry is held in the current by a sufficiently long rope (yaw rope) and "swings", driven by adjusting a rudder in the current from bank to bank.

Roller ferries are guided over rollers on a taut rope that is stretched between the banks. The ferry is propelled in the desired direction by adjusting a rudder to the current.

3.2.2 Non-free moving ferries with own drive

Cable and chain ferries. These ferries are guided along a rope or chain stretched between the shores, which serves as a drive and prevents the ferry from drifting. They are driven by a cable or chain winch connected to a motor.

Overhead line ferries are electric ferries which receive their electrical energy for driving the cable or chain winch via a supply line. The supply line is held on a suspension cable which is stretched over the water.

Figure 5 Guide chain of a chain ferry across the Saale river. [9]

Figure 6 Catenary ferry as chain ferry across the Saale river. [10]

3.2.3 Free-moving ferries

Free-moving ferries are all other ferries that use their own motive power and steering equipment to navigate freely on the water.

Drives are propellers with rudder systems as well as combined rudder propellers, which are driven by motors, by sails or by muscle power. Motors for ferries are combustion engines or electric motors. The energy supply of a ferry depends on the installed power of the propulsion system.

3.2.4 Loading of ferries

The type of docking at the dock/jetty/berth is important for walking on, driving on or loading ferries. Passengers of urban ferries are mostly pedestrians and cyclists. Therefore, it is advisable to enter from the side or from the front. When transferring cars and trucks, double-ended ferries are common, as it is not possible to turn vehicles on the ferry. In the case of cable or chain ferries turning the ferry is also impossible.

3.2.5 Touristic aspects of ferries

In coastal and port cities and in cities along rivers, ferries are a necessary and traditional means of public transport. Furthermore, ferries offer attractive opportunities for cities and transport companies to use them for tourism, with a positive impact on citizens and guests.

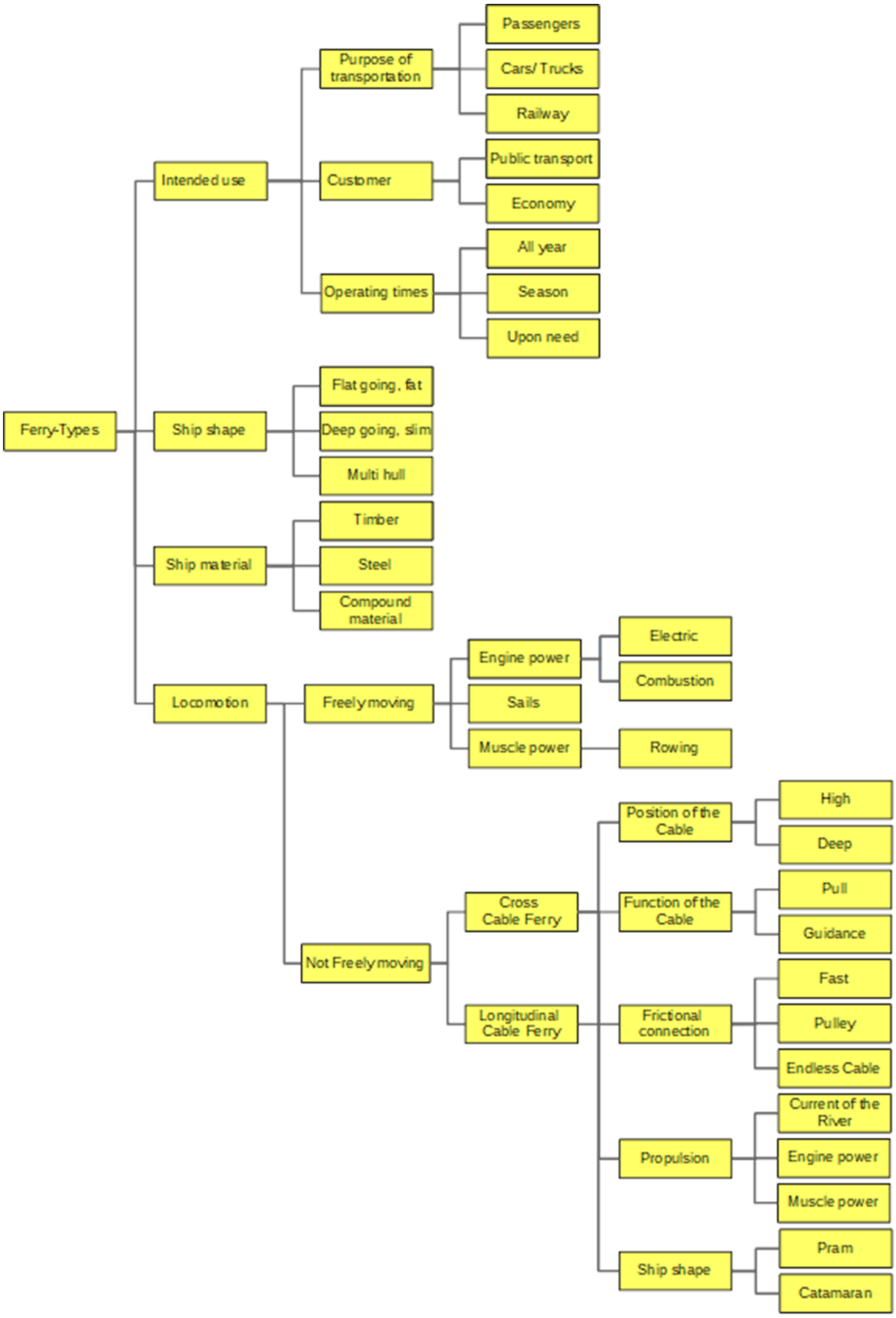


Figure 7 Classification of ferries. [11].

3.3 Use of ferries

What role do ferries play in traffic and urban transport? Are ferries used? How often are ferries used?

Statista conducted a survey among 1,016 respondents of the German-speaking resident population in the period from 16.02.2017 to 22.02.2017. The question was asked: Have you travelled on a ferry in the last 2 years? [12]

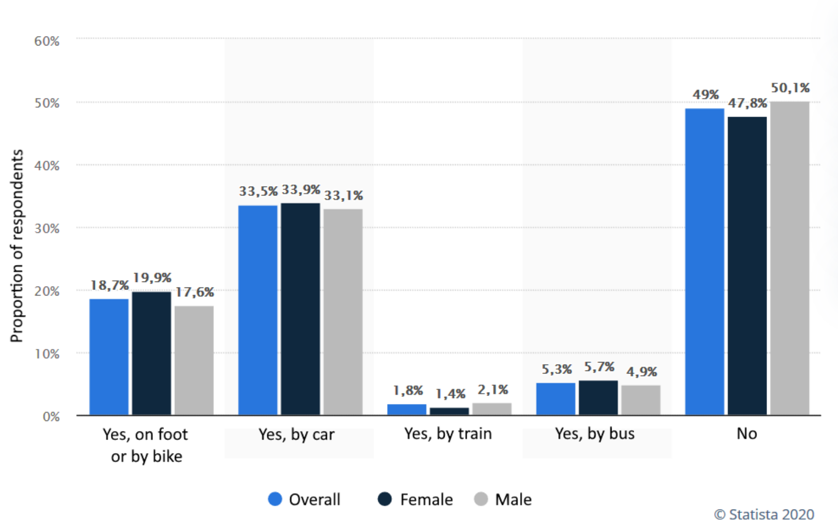


Figure 8 Result on the use of ferries [12]

More than half of the respondents have used ferries. Use as pedestrians, cyclists and motorists suggests that ferries are used for commuting to work or for frequent trips. This suggests that ferries still play an important role.

3.4 Benefits and added value of e-ferries

There is an unmistakable trend towards the electrification of ferry connections because in addition to some technical and economic challenges, electric ferries offer many advantages. The potential for electrification of free-moving ferries is great, but most ferries in service are still conventionally powered by combustion engines.

The use of this potential is demonstrated by a larger number of cities and ferry companies in the Baltic Sea region and in Northern Europe, which are planning projects to build new electric ferries and to convert to electric propulsion. A development towards electric mobility in ferries in the Baltic Sea region was well observed over the course of the "BSR electric" project: At the start of the project in 2017, only a few electric ferries were in operation in the Baltic Sea region and some were in the planning stage.

The city of Oslo, for example, planned to electrify ten ferries operated by the "Ruter" public transport company, which had previously been powered by LNG. At the time of writing, our project partner from Oslo reported that two of the electric ferries and the electric port infrastructure had already been put into operation. [13]

Although Oslo already had a very advanced technology with the LNG-operated ferries, electrification was pushed forward. Oslo was awarded the title of "Environmental Capital" by the European Commission in 2019. Ferry traffic in the Oslofjord is an important part of public transport in Oslo and for the entire metropolitan region. Electrification is therefore a high priority. By converting existing ferries to electric operation, local energy sources can be used, costs saved and plans for electrification in Oslo can be implemented more quickly.

Figure 9 Electric ferry "Dronningen" at the fast charging tower, Oslo harbour. [13]

The Polish project partner, the city of Gdansk and other cities in the Baltic Sea region are also pursuing ambitions and plans for an electric ferry connection. The city of Turku in Finland electrified the ferry boat "Föri", a chain ferry that crosses the Aurajoki River, approx. 100 meters, as early as 2018. "Föri" has cult status in Turku.

Figure 10 10 Ferry "Föri" in Turku. [14]

Figure 11 Crossing the Aurajoki River in winter time [15]

In other regions and cities of the Baltic Sea region and Northern Germany, too, plans and implementations of the electrification of urban mobility are underway. Specifically, best-practice examples were examined during the project period and the procurement process of a modern electric ferry as a replacement for a diesel-powered ferry was accompanied.

3.4.1 Advantages of electric ferries

- do not cause local emissions,
- make no noise and produce no exhaust fumes;
- save CO2 in about three times the weight of the saved diesel;
- enable the use of local renewable energy sources;
- have a positive image for the city and the region;
- improve passenger comfort;
- improved working conditions through easy operation and modern technology;
- create a reference and model for other communities;

Furthermore, electric ferries deliver

- Possibilities of tourist use,

- Use of existing transport routes,
- Relief of the transport network,
- Deceleration of regional transport,
- harmonious integration into the regional landscape,
- Creation of demand, added value and jobs.

3.4.2 Environmental policy relevance

The environmental policy relevance for electric mobility in general and for electric ferries in particular is outlined by the United Nations Framework Convention on Climate Change (UN-FCCC) and the follow-up conferences such as the 21st Conference of the Parties (COP21). Within this framework, international targets to limit global warming to less than two degrees were agreed. At the 48th session of the IPCC (Intergovernmental Panel on Climate Change) in Incheon, South Korea, on 6 October 2018, another warning was issued against the effects of global warming caused by industry, agriculture, energy, transport and infrastructure [16], [17]. The member states are called upon to gear their industrial, transport and energy policies to this scenario, to define corresponding political goals at national level and to create framework conditions for strict implementation.

At the local and regional level, local authorities have drawn up catalogues of measures for the environment, infrastructure, the economy and others for implementation. Electric mobility has great potential for implementation. Electric ferries, especially all-electric ferries, do not cause any emissions during operation and thus offer an effective measure for the implementation of the UNFCCC goals at local level.

3.4.3 Relevance for research and development

The transformation of the transport sector using electrical energy requires a constant search for new solutions as well as development, advancement and improvement. For cities in the Baltic Sea region with a scientific and technical potential, electric mobility in combination with maritime economy offers new opportunities for education, research and development. Electric ferries are an interesting object for testing and implementing new technologies.

Topics with technical and social relevance include

- Alternative fuels, energy converters for electric drives,
- Hydrogen, hydrogen derivatives, methanol, ammonia as fuel alternatives,
- Fuel cell systems for electric shipping,
- Lightweight construction and new shipbuilding designs,
- optimized hydrodynamics and effective drives,
- improved propulsion systems,
- Remote maintenance, digital ship inspection for safety and maintenance,
- Autonomous maritime systems, driver assistance systems,
- improved energy storage and energy converters,
- Extraction of operational data of electric ferries and data as an economic good,
- Training of skippers for electric ferries and electric ships.

3.5 Procurement of an Electric Ferry - Case Study

One of the reasons for the commitment to the "BSR electric" project, as well as for the case study, was the planned replacement of an electric ferry for a now more than 20-year-old ferry on a traditional inner-city ferry line.

Both the hull and the main engine were in a condition that made an overhaul no longer seem sensible. Therefore the purchase of a modern electric ferry had been considered for some time. It was a fortunate circumstance that as the "BSR electric" project progressed, the procurement measures could be advanced and incorporated into the work.

Historical context of the ferries as an example

The question of procuring a ferry, as opposed to an alternative, such as a bridge or a tunnel, must always be answered against the background of local and historical conditions.

On the lower Warnow river (Unterwarnow) near Rostock there have always been several ferry connections between early settlements and the later villages Gehlsdorf, Oldendorf and Hohe Düne as well as Marienehe, Schmarl and Warnemünde. Today, these places are districts of Rostock.

The shipyards as well as their businesses and industries were located along the Warnow river and in this respect, ferries were an important means of transport for professional and company traffic also in the recent past.

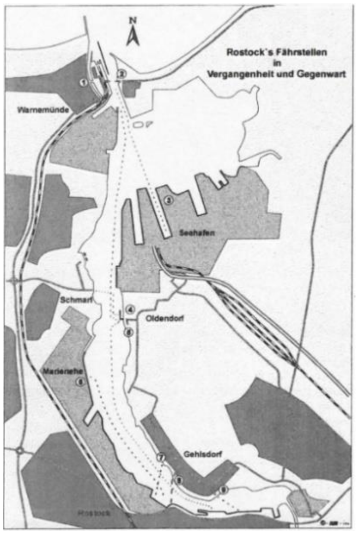


Figure 12 Ferry connections on the Unterwarnow. [11]

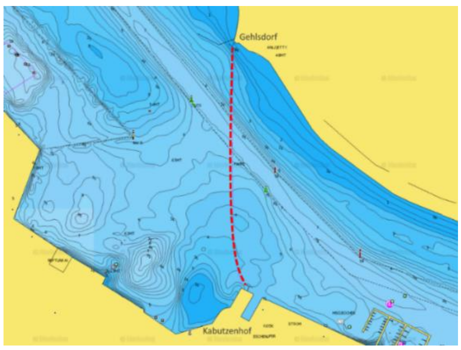


Figure 13 Ferry line across the Warnow. River. [18]

The ferry connection between the at that time still independent municipality Gehlsdorf and the city of Rostock is existing since the year 1880 and except for a few interruptions (strong ice drift) the traffic was maintained. At times even a car ferry was in operation on this line.

Figure 14 Wagon ferry with steam operation "Gehlstorf". [19]

Due to the expansion of traffic by motor vehicles at the end of the 19th century, combined with greater vehicle weights, consideration was given to replacing ferry crossings with bridges at exposed locations, for example in the 1920s and late 1960s.

Between Schmarl and Oldendorf there was a temporary ferry connection across the Warnow, which was discontinued after completion of the Warnow Tunnel in autumn 2003. Ferries on the Unterwarnow about the times: [11], [20]

- Steam ferry "Gehlsdorf", from 1907 to about 1955, built by the Rendsburger Schiffs- und Maschinenbau GmbH, 120 BT, for the city of Rostock.
- Ferry "Willi Schröder", 1955 to 1963. 1954 built at the VEB shipyard Neptun, Warnemünde (B-Nr: 859), 226 BT, for the city of Rostock.
- Ferry "Albert Schmidt", 1963 - 1991. 1955. 1995 to Spain, sunk there (probably 2001).
- Ferry "Gehlsdorf", until 1991, in the meantime.
- Ferry "Gehlsdorf", built 1998 and still in service today.
- Electric ferry "Gehlsdorf", new building, planned to be put into service in 2021.

Figure 15 Ferry „Willi Schröder“. [21]

Figure 16 Ferry „Albert Schmidt“. [22]

Figure 17 Ferry boat to Gehlsdorf, 1970s. [23]

Figure 18 The ferry „Gehlsdorf" at the pier. [24]

The decline in demand for local passenger ferries and ferry connections continued due to the rapid development of public transport and individual transport. The public only notices such developments when passengers who depend on this ferry service are affected. This is when demands are made to continue ferry operations. Cities and operators are trying to counteract the economic pressure and secure the necessary transport with smaller vehicles and a restricted timetable. The ferry connection Kabutzenhof - Gehlsdorf, as a remaining ferry in the inner-city area, is such an example.

Savings potentials of an electric ferry as an example

The following example is given to estimate the savings potential:

- Steel catamaran for up to 80 passengers and 15 bicycles,
- Propulsion with two 37 kW rudder propellers, powered by batteries,
- Additionally equipped with 36 solar modules for permanent recharging and to extend the driving distance.

An electric ferry of this size may also have the following driving profile as shown in the table:

Circulations	
Monday-Friday	35
Weekly x 5 =	175
Saturday, Sunday, public holiday	4
Weekly x 2 =	8
per week	183
per year x 50=	9,150

Operating hours	Per day	Per week
Monday-Friday	14	70
Saturday, Sunday, public holiday	8	16
	week	86
Consumption	**litres**	**kg**
per hour	8	
per week	722	
per year	36,120	
CO_2 savings per year		95,718

CO_2 emission per litre of diesel: 2.65 (kg/kg)

Diesel consumption (100 HP) approx. 5. 9 litres/op. hour

An electric ferry of this kind can carry more than 500 passengers a day in a quiet, environmentally friendly and comfortable way, saving around 36,000 liters of diesel fuel and around 96 tons of CO_2 per year.

3.6 Observation and experience in the procurement of urban electric ferries

Motivated by political impulses, recommendations, guidelines and actors, environmental awareness in society has changed over the past decades. The progressive electrification of means of transport is an expression of this change and it is supported by the availability of the technology.

Local authorities and transport companies see the procurement and operation of electric ferries as an opportunity to implement their goals and agendas for environmental protection and the reduction of climate-relevant emissions.

The increased use of regional regenerative electrical energy sources as well as the intelligent combination of technical resources also offers potentials for saving costs for ferry operations.

The procurement of an electric ferry represents a complex task for municipalities or transport companies, as it

- represents a major investment with considerable financial outlay,
- must be politically desired, supported and affordable,
- must be procured under competitive rules,
- is accepted by passengers and can be integrated into local transport,
- must be technically feasible and can be operated in an economically and ecologically sustainable manner over the period of use,
- requires special knowledge, which can be

It must also be remembered that free-moving electric ferries are complex technical structures that always require a landside infrastructure and an additional charging infrastructure. Ship and port (pier) form one unit.

Transportation by water poses a safety risk for people, goods and the environment. Ship accidents on shipping routes are complex and expensive incidents with consequential damage and costs due to breakdowns as well costs caused by blockage of waterways and for the repair of the damage. Ferry operations are therefore subject to strict legal requirements.

In the case of a new establishment, ferries with a similar initial situation will be used, e.g. intended use, sailing profile, waterways or traffic network. In the case of replacement, these criteria can be taken from ongoing operations. In any case, the stakeholders are well positioned if they consult technical expertise in good time for their decisions and planning.

3.6.1 Conditions and rules of the procurement process

The procurement of goods and the award of contracts for public authorities are subject to conditions regulated in the EU. Contracts of medium and higher value are awarded in the course of competitive procedures (tenders). There are different types of procedures for public procurement. There are exceptions, e.g. for the purchase of real estate, for extremely urgent cases and cases where there is only one possible bidder. The usual way is the tender. [25]

The law governing the conduct of tenders is the "Act against Restraints of Competition", the purpose of which is to prevent the abuse of a dominant position by one or more companies. [26]

This law regulates the types of procedures that are used for the award of public contracts. The open procedure and restricted procedure, which always require a call for competition, are available to contracting authorities at their discretion. The other types of procedure are only available to the extent permitted by this Act. Further details on thresholds, recurring purchases, electronic procurement systems, information, cross-border procedures, refusals and the like can be found on the relevant websites, such as [27] and [26].

3.6.1.1 In open procedure

The open procedure is a procedure in which the contracting authority publicly invites an unlimited number of undertakings to submit tenders. Bidders can submit tenders. This procedure is the most frequently used.

3.6.1.2 In restricted procedure

The restricted procedure is a procedure in which the contracting authority, after a prior public invitation to tender, selects a limited number of enterprises on the basis of objective, transparent and non-discriminatory criteria (a "contest for participation") which it invites to submit tenders. In principle, anyone can apply to participate in this contest.

3.6.1.3 The negotiated procedure

Negotiated procedure is a procedure in which the contracting authority invites selected enterprises, with or without a call for competition, to negotiate with one or more of these enterprises about the tenders.

Here, too, anyone can apply to participate. However, only selected participants are invited to submit an initial bid and to negotiate. Procurement agencies use this procedure if the nature and complexity of the procurement requires negotiations. It is often the standard procedure in the transport, postal services, defence, security, water and energy sectors.

3.6.1.4 The competitive dialogue

Competitive dialogue is a public procurement procedure aimed at identifying and defining the means of best meeting the needs of the contracting authority. Following a competitive tender, the contracting authority opens a dialogue with the selected companies to discuss all aspects of the contract award.

This procedure is used for particularly complex contracts if the contracting authority is unable to specify the technical means and the legal and/or financial conditions to meet the needs and objectives for the formulation of a contract. The implementation is carried out in a transparent, competitive procedure "in dialogue" with the bidders. In practice, this procedure is not very common. This procedure is not open to contracting authorities of the sectors mentioned.

If interpreted, this method could be used as a tool for needs assessment, market research and information gathering. However, there are also possibilities to involve neutral providers of expertise.

3.6.1.5 Innovation partnership

The innovation partnership is a procedure for the development of innovative supplies, works or services not yet available on the market and for the subsequent purchase of the resulting services. Following a competitive bidding process, the contracting authority negotiates in several phases with the selected companies about the initial and follow-up offers.

Innovation partnerships are used when goods or services are procured that are not available on the market and may first have to be developed.

3.6.2 Qualified offer

As already mentioned, the procurement of an electric ferry is a complex and multi-dimensional project. The timely inclusion of expertise can avoid costs and time delays.

The method by which this can be achieved is similar to the competitive dialogue mentioned above. In concrete terms, this means that, for example, a shipyard is involved in the preparation of a feasibility study, on the basis of which a so-called "qualified offer" can be made. Through this dialogue and its results, the tender documents can be formulated in a bidder-friendly manner, the state of the art can be taken into account and feasibility and implementation can be ensured.

The awarding authority (the municipality) is thereby relieved and wins additional bidders for the tender and competition. This procedure gives bidders the scope to formulate feasible initial offers. The invitation to the tender itself takes place in a negotiated procedure, in which previously selected bidders participate.

Because it can be assumed that the participating bidders know and master the state of the art, the awarding authority does not run the risk of distorting competition. The awarding authority is relieved of a task which requires a high degree of specific qualification on the part of the agents involved, but which is rarely demanded. The contradiction between the frequency of the task and the degree of required qualifications from outside the field of expertise at the awarding authority can be solved by a qualified offer.

3.6.3 Qualified functional tender

An alternative to the "qualified offer" could be the "functional tender". The municipality independently formulates its requirements on the basis of a requirement profile for the electric ferry. The municipality then discusses the requirements profile with a trusted expert or with a selected qualified shipyard.

The preparation of the functional tender offers the chance for revision as well as for new concepts for implementation.

Criteria for the development of a requirement profile as well as for the definition of the electric ferry for urban traffic should at least consider these parameters.

- Intended purpose and place of use (waters, route, etc.),
- Seasonal, weekly and daily peak times,
- Number of passengers, parking spaces and their preferences,
- ship-port-infrastructure dependencies,
- Driving profile (power, acceleration, speed, energy consumption etc. over time),
- Weather and climatic conditions,
- Legal framework,
- Concessions, integration into the public transport system,
- Guarantees, useful life, service, etc.

In the case of a replacement for a vehicle of an existing ferry line, these specifications are available or can be taken up during operation.

Even in the case of a functional tender involving a shipyard as a potential competitor, it can be assumed that bidders who are subsequently requested to bid know and master the state of the art and can formulate and submit independent initial offers. The further procedure of the invitation to tender takes place in a negotiation procedure, for which in principle any shipyard can apply and be selected.

3.6.4 Evaluation of the bid

In order to select the winner of the bidding competition, the incoming offers must be evaluated. The evaluation of the incoming offers is based on evaluation criteria (evaluation matrix), which should be established in connection with the preparation of the tender documents.

Here the same boundary conditions apply with regard to the technical qualification. In addition, there are more general criteria for the evaluation of offers for the electric ferry in connection with its use in urban traffic. An optimal way to formulate the criteria would also be a trustful cooperation with a qualified supplier, a shipyard or an expert, as in the case of the "Qualified Offer" or the "Qualified Functional Tender".

Incoming offers are evaluated on the basis of the evaluation matrix. The more detailed the evaluation matrix is, the more accurately a bidder can be selected. If only a few criteria are defined, it may be that all bidders meet the criteria and no selection is possible.

A systematic procedure for setting up an evaluation matrix should include

- bid price,
- the points of section "Qualified functional tender",
- creditworthiness and reliability of the bidder,
- Social and labour law criteria,
- Construction time and deadlines,

It makes sense to evaluate points by grouping and prioritizing the criteria and weighting them according to group and priority. An evaluation with the matrix ends in the simplest case with group scores and a total score.

Technically speaking, a spreadsheet program, e.g. Excel, is used as the matrix. Graphical evaluations are then also possible, e.g. "spider diagrams", in which the evaluation of the groups spans a "spider web", which enables a very clear evaluation and facilitates decision-making.

The contradiction between the qualifications and the specialist expertise required to evaluate the tenders should be resolved by setting up a qualified evaluation matrix in the phase of preparing the tender. In this way, the necessary consulting effort can be absorbed.

The evaluation of bids is in the hands of the awarding authority (e.g. local authority). The awarding authority bears the responsibility and makes the decision. However, as mentioned above, he can include neutral, external expertise in this process. While the awarding authority may cooperate with an institution from the group of bidders in the phase of developing a "qualified functional tender", this is not advisable for the phase of evaluation.

3.6.5 Independent technical tendering bodies

The presentation of the function of expertise and the position of trust for

- Preparation of qualified functional tenders,
- Evaluation of qualified functional tenders before sending them out,
- Creation of evaluation criteria and the evaluation matrix,
- Evaluation of received offers and proposal of the winners,

would be most easily achieved by an independent institute. This institution would be able to draw up the technical specifications for the municipalities and conduct the economic dialogue between the municipality and the yard. If necessary, this institution can take over the construction supervision for the municipality.

Ideally, this institution could be created as a public body, associated with the public authorities or as a private institution with a neutral status and a corresponding association. The tasks and characteristics should be as follows:

- Description of the vessel,
- Description of the ship/port infrastructure system and its operation,
- Expertise and skills of a design office,
- Expertise of a tendering office,
- Preparation of tender documents in accordance with the regulations

(with constantly changing regulations).

Design offices are predestined candidates, however, a conflict of interest can arise here, because it can be assumed that the business model is the marketing of design hours. In contrast, the interest of the awarding authority is to create a simple and cost-effective solution.

Awarding authorities and tendering offices only act on the level of processing, formalities, award guidelines, deadlines, conformity of the tenders with legal and funding requirements, etc. Technical and specialist expertise must be supplemented.

The most important requirements in the procurement (of electric ferries) are expertise, neutrality, avoidance of conflicts of interest due to sensitivities and preferences of parties.

Summary:

- Position of trust through neutrality and independence from bidders (shipyards),
- Technical know-how for the development of shipbuilding technical specifications, provision of sufficient design knowledge,
- Ability to create detailed specifications and qualified functional tendering,
- Avoidance of conflicts of interest,
- Representation of the interests of the awarding authority, the investor, the municipality etc., in particular adherence to budgets,
- Function of a "technical broker".

3.6.6 Operators for electric ferries

If one looks beyond the tendering process into the phase of operation of the electric ferries, the question of an independent operator who can relieve municipalities of this task arises. Currently common models are to award the operation of the ferries to a retailer, e.g. Weiße Flotte, Norled, Finnferries via concessions. The principle: The municipality awards a concession to a shipping company which implements the operation according to the specifications. Or the concession is granted to a transport company, which subcontracts the shipping company, which realizes the operation according to the specifications of the transport company.

Another well-known model is that of operating companies as practised in cities like Hamburg. One example of these owner and operator pools of ships is the Hamburg fleet.

A key characteristic of such an independent operating company is to generate greater economic efficiency in order to ensure ferry services. This enables sustainable operation and innovation of the fleet. Local authorities receive ferry services "as-a-service".

In contrast to smaller companies, independent owner and operating companies are in a stronger position to introduce innovations and new technologies, to carry out feasibility studies and to carry out procurement processes independently. Furthermore, they are in a better position than smaller companies and shipping companies to carry out concession management, ferry operations and the entire business administration.

3.6.7 Monitoring of procurement processes - examples

The procurement of an electric ferry, with its complexity as a multidimensional process, places high demands on those responsible and the stakeholders. Errors lead to additional economic expenditure and to delays. Therefore, an optimal approach is of great interest to the responsible actors and stakeholders at the various levels. What could be an optimal approach?

In order to try to answer the question of the optimal procedure, literary research and exchange of experience with project partners was carried out, information from comparable projects was used and evaluated. In addition, personal interviews were conducted with stakeholders on both sides of the tendering process.

In the following, the information obtained is to be presented in a systematic and anonymous way. This neutral approach should enable the information to be used for the own project and to learn from mistakes and successes.

Example 1

Municipalities do not have all or any resources for the procurement of such complex means of transport as ferries. Municipal administrations, including most transport companies, seldom do this, and it is not worthwhile keeping special resources in the regular business. The port captain of the municipality has nautical knowledge and relevant experience. Often, however, he does not have knowledge and experience of shipbuilding and ship design. He acts as a technical advisor to the municipality. The analysis and evaluation of the bids in a tender for the decision of the municipality to award the contract differ greatly from the port captain's normal field of work and the necessary resources are not available.

Experience has shown that the divergence between the expectations of the municipal administration and the possibilities of the port authority leads to excessive challenges and frustration.

Example 2

A design office was commissioned for the technical preparation of a tender document. The office developed a visionary document that was too extensive and oversized from the point of view of the municipality. Both the ferry and the necessary infrastructure were beyond the budget. The client's contractors were looking for a simple solution that would take into account the traditional operation of the ferry and the local conditions. For the tender, the document was nevertheless used (because of the amount of work involved).

As a result, the bidders who were asked did not submit offers on the basis of the tender document but made alternative offers. This posed further challenges for the awarding authority in evaluating the different, non-comparable offers. Finally, new offers were requested on the basis of an alternative offer, so that an evaluation and selection of a bidder for the contract was possible. This delayed the process and resulted in additional costs.

3.6.8 Proposal for a procedure

Procedure/process level	Measures	Responsibility
Tender documents	-qualified tender, -Qualified functional tendering	- Municipality/local authority (awarding authority), -design office, -independent body -shipyard (cooperation)
Negotiated procedure	- evaluation of tenders	- Municipality/local authority (awarding authority), -independent body
Construction phase and handover	- construction supervision	- Municipality/local authority (awarding authority), -independent body
Operation	-Initial operation, -Regular operation -Commune	- Municipality/local authority (awarding authority), -Communal transport services -Shipping company/independent owner and operating company

3.7 Financing of electric ferries

In a concrete procurement project for an urban electric ferry, it became apparent that no adequate funding instruments were available to municipalities or transport companies for the procurement, in particular of an electric watercraft for public transport in the period under consideration. In principle, it is possible to present a co-financing of electric mobility solutions with the help of general support instruments such as climate pacts, climate protection programmes (e.g. climate protection guideline of the state of Mecklenburg-Western Pomerania). Unfortunately, special programmes for the procurement of electric ferries are not available in Germany (e.g. Norway is a pioneer in this field). On the other hand, there have been and still are a number of funding opportunities for land-based electromobility, electric municipal vehicles and e-buses for local transport.

There also seems to be a gap on a European-transnational scale for electric shipping. Although programmes for clean shipping are available, there are considerable differences between inland navigation and large-scale maritime shipping. In the following, some statements and information are compared.

3.7.1 Challenges for shipping in the EU

Initial situation	→	Requirement
• Gaps in EU investments are a competitive disadvantage • Lack of liquidity, creditworthiness of the market • Restrictions in public budgets • Financial and non-financial hurdles - EU guarantees	→	• European Investment Bank (EIB) • European Investment Fund (EIF) • Cohesion Fund • Better conditions for investment needed •

The situation and implications for maritime freight transport, for the shipping industry and for inland and ferry shipping are comparable:

Challenge	→	Impact
• Competitiveness • Availability of financing • ECA (environmental zones) with "driving ban" in the North Sea and Baltic Sea • Limited capital and tighter selection criteria for creditworthiness - New regulations require technological changes,	→	• New regulations require technological changes, • New technologies -require upfront costs, -but do not offer any upfront advantage, • Financing for investments in shipping is more difficult

3.7.2 Financing for 'green'/clean shipping on an EU scale

What European (EU) and national funds are available to support this area?

3.7.2.1 European Fund for Strategic Investments (EFSI, and EFSI 2.0)

[28]

1 European Fund for Strategic Investment (EFSI) • Green Shipping Loan Programme • Connecting Europe Facility(CEF) • Framework agreements: EIB and private banks	EUR 750 million (project) EUR 40 million (project)	Longer funding period
2 Partnership: European Bank for Reconstruction and Development International Maritime Organization	Promoting sustainable maritime transport	Major investment targets
3 EU Strategy for the Baltic Sea Region (EUSBSR)	Part of the European Structural & Investment Funds Programme 2014-2020	Greater transparency in investment decisions
4 Horizon 2020 (2014 – 2020)	EUR 80 billion	More detailed definition of the allocation
5 European Sustainable Shipping Forum (ESSF)	-Use of LNG in the EU -Transport research and innovations	Greater focus on sustainable projects

The **European Fund for Strategic Investment (EFSI)** is oriented towards these main fields:

- research and innovation,
- digital technologies,
- Low-carbon economy,
- sustainable management of natural resources,
- Small and medium-sized enterprises.

A new feature of EFSI2.0 is increased local technical support and networking through the European Investment Advisory Hub. [29]

3.7.2.2 Green Shipping Loan Programme

The included Green Shipping Loan Programme (EUR 750 million project) promotes "green projects" including pollution prevention and clean transport.

3.7.2.3 Connecting Europe Facility

Also included in EFSI is the Connecting Europe Facility (CEF) (EUR 40 million project). CEF is a combination of EU funds and has approximately EUR 26 billion available for transport infrastructure for the period 2014-2020. CEF provides funding:

- Renewable energy, focus on clean maritime transport, "CEF Energy": EUR 4.7 billion,
- "CEF Telecom": EUR 500 million,
- Clean transport modes, "CEF Transport": EUR 23.7 billion.

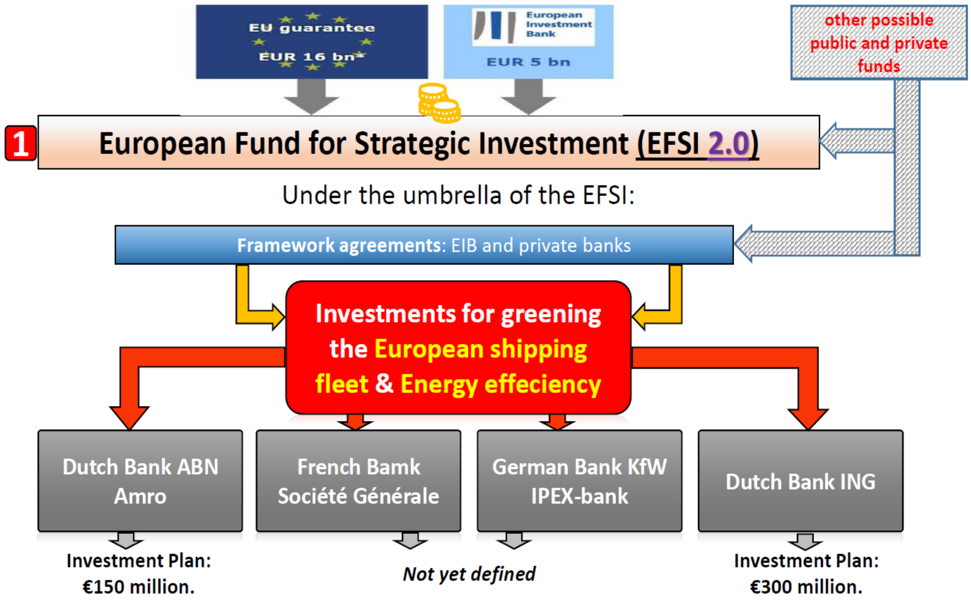


Figure 19 Structure of EFSI 2.0. [28]

3.7.3 Best practice for funding through the EFSI

3.7.3.1 *Scandlines*

- Use of the CEF (Connecting Europe Facility),
- Green Initiatives (environmentally friendly operation),
- **EUR 6.3 million** from the EU for the installation of scrubbers and hybrid systems.
- The hybrid system combines conventional diesel propulsion with electric batteries (see chapter Examples),
- Scandlines was the first shipping company to implement hybrid technology on this scale,
- Additional co-financing of EUR 2.3 million for the installation of the hybrid system. [28]

3.7.3.2 *Brittany Ferries*

The European Investment Bank (EIB) and Brittany Ferries announced in December 2017 the first financing to be implemented under the Connecting Europe Facility (CEF) and the Green Shipping Loan Programme. Brittany Ferries financed the first LNG-powered ferry, which entered service in April 2019. [28]

3.7.4 Support for inland waterway transport

Urban electric ferries are operated on inland waterways. Therefore, it is obvious to investigate the possibilities for inland waterway transport. The Waterways and Shipping Administration [30] announces the following possibilities through its media. On the basis of the above-mentioned funding possibilities, the procurement and financing of an urban electric ferry can only be developed with some creative effort, but it is often not possible to map it completely.

3.7.4.1 National support programmes

- Promotion of transshipment facilities for combined transport,
- Promotion of innovation in shipbuilding, including for inland waterway vessels,
- Shipbuilding subsidies: since August 2019, the subsidies for the construction of sea-going inland waterway vessels have been extended to all inland waterway vessels,
- Support programme for the sustainable modernisation of inland waterway vessels,
- Promotion of training and further training in German inland navigation,
- Innovative Port Technologies Support Programme (IHATEC),
- Support programme market activation of alternative technologies for the environmentally friendly on-board and mobile shore power supply of sea and inland vessels,
- Promotion of consultancy and training for inland navigation companies (BAFA), subsidy for the costs of management consultancy, (50%/75%) for general consultancy, economic, financial, personnel, organisational, technological and innovation consultancy,
- Energy consulting and promotion for inland navigation companies, short study "Energy consulting in German inland navigation", energy consulting for medium-sized companies,

European funding programmes

- PLATINA Project: European funding database for research, technological development and demonstration for the inland waterway sector,
- RIS equipment programme of the Serbian Waterways Directorate. The Serbian Waterways Directorate (PLOVPUT) has launched a RIS equipment programme in which German inland navigation can also participate.

3.7.5 Conclusion

At national and EU level, there are currently no special programmes for the procurement of urban electric ferries (Germany). Possibilities for partial financing can be considered through general programmes for climate protection, research promotion or investment promotion. It should be noted that a number of these programmes and guidelines will end in 2020. Against this background, possibilities for private financing within the framework of operating or owner companies (see the section above) should be examined in order to implement solutions promptly.

3.8 Checklist "Electric Ferry" for stakeholders

On the basis of research, interviews with stakeholders and consultations with qualified bodies, statements, questions and advice were compiled and assigned to the sub-items. This checklist is a condensation, a summary of the practical experience gained from the tendering process and the operation of inland electric ferries.

3.8.1 Procurement process

- ✓ Define a requirement profile of the electric ferry (ship) as precisely as possible.
- ✓ Define the periphery and infrastructure (country) as precisely as possible.
- ✓ Begin planning in good time.
- ✓ Inform yourself about potential suppliers at an early stage.
- ✓ Use the exchange of experience with transport companies that already operate electric ferries.
- ✓ Use the experience and knowledge of the suppliers for your solution.
- ✓ Formulate the tender.
- ✓ Estimate the cost framework and define the budget.
- ✓ Define the required type of tender.
- ✓ Draw on expert knowledge and use it as a neutral partner.
- ✓ Keep the bid invitation within the budget.
- ✓ Avoid conflicts of interest in competition.

3.8.2 Environmental relevance

- ✓ Consider zero emission solutions.
- ✓ Aim for sustainability and low impact.
- ✓ Make this the default option for procurement.
- ✓ Reward the search for environmentally and climate-friendly solutions.
- ✓ Launch competitions and give awards and bonuses.
- ✓ Offer incentives and special prizes for switching to green transport.

3.8.3 City/municipality transport department

- ✓ Electric ferries will be used to achieve the ambitious goals set out in the European Commission's White Paper on Transport and the Reduction of CO2 Emissions. Communicate the innovation appropriately in the community/city.
- ✓ Develop a long-term vision for the development of the transport system.
- ✓ Plan replacement investments with the operator/concessionaire in time.
- ✓ Gain basic knowledge at an early stage, contact potential suppliers of electric ships.
- ✓ Ensure that you have the right expertise and sufficient administrative capacity.
- ✓ Communicate with urban planning to integrate the electric ferry into the public transport system.
- ✓ Create incentives to use the electric ferry.
- ✓ Grant incentives or even privileges for the ferry operator, e.g. low rent, sale on board, catering, (so-called "jug justice").
- ✓ Plan alternative uses of the electric ferries for tourist purposes within the framework of major public events.
- ✓ Check possibilities for low energy prices, e.g. by using the night hours for recharging.

3.8.4 Spatial and urban planning

- ✓ If necessary, plan for the provision of areas and real estate for the investment in an electric ferry/electric water taxi (access road, building site for infrastructure).
- ✓ Take into account the expansion of the electric ferry connection with regard to the load or relief of the transport system.
- ✓ Communicate with the transport department regarding the traffic planning of the municipality.
- ✓ Investigate traffic volumes, through adjacent residential and commercial areas.
- ✓ Use and communicate with map displays as a planning aid and means of communication.
- ✓ Use and communicate story maps as a dynamic planning aid for recording changes over time.
- ✓ Include historical backgrounds in the planning process.

3.8.5 Public perception

- ✓ Promote your electric ferry.
- ✓ Make the passengers and guests of the city aware of the innovation.
- ✓ Point out the positive effects of the electric ferry on mobility and the environment, on health, well-being and beautification of public spaces.
- ✓ Inform about interesting details and superlatives.
- ✓ Involve the public in your goals.
- ✓ Give opportunities for citizens to be proud of the community.
- ✓ Offer incentives and recognitions for users and operators of the electric ferry.
- ✓ Include historical background in the planning.

3.8.6 Technical planning

- ✓ Plan time for the procurement process, consider delivery times and terms. Ferries are individual single products, shipyards have limited capacities, manufacturers have specialisations.
- ✓ Electric ferries have technical constraints and special features. Determine as precisely as possible the operating profile and the driving profile of the planned electric ferry.
- ✓ Create a requirement profile for the electric ferry. Consider the local transport plans of the municipality. Define goals in terms of use, ranges, daily charging times (timetable, work times).
- ✓ Find out about the service life, technical boundary conditions and procurement times of the most expensive components of the electric ferry.
- ✓ Check the infrastructure conditions: Presence of electrical supply lines, voltage level, current intensity, electrical current for charging etc.
- ✓ Use technical expertise to prepare the technical specifications for the tender.
- ✓ Contact the network operator and relevant stakeholders early on to secure the technical and charging infrastructure.
- ✓ Are there reduced grid fees for the electricity consumption of the electric ferry? Is there a backup system for possible grid failures?
- ✓

3.8.7 Daily operation and navigation

- ✓ Inform the skipper about the driving behaviour of electric ferries.
- ✓ The driving behaviour affects the battery life.
- ✓ Schedule training and instruction.
- ✓ Ensure a clear view in the passenger compartment to increase safety and prevent vandalism and material damage.
- ✓ Plan the possibility of remote diagnosis, operating data acquisition and forwarding to a server for planning maintenance and repair.
- ✓ Adapt the training level of the skippers to the new conditions.

3.8.8 Planning and tendering: preparation

- ✓ Include expertise and specialist knowledge in the planning and preparation of the tender, avoid duplication of work.
- ✓ Avoid conflicts of interest between actors and suppliers.
- ✓ Acquire basic expertise on: technical issues and the tendering process.
- ✓ Involve stakeholders such as public transport, shipping companies, operators, experts and shipyards as well as independent expertise.

3.8.9 Planning and tendering: ship

- ✓ Determine a travel profile, an intended use for the design of the ship and the energy consumption, capacity of the ship, passengers, other loads (bicycles, prams, luggage).
- ✓ Consider additional types of use, e.g. for tourist trips.
- ✓ Define the type of ship (front/rear / side loading, catamaran, pram, etc.), decide for one-man operation, safety and comfort on board, mooring technology: magnetic mooring lines.
- ✓ Consider experience and wishes of the operator for change.
- ✓ Keep in mind the meteorological conditions at the turn of the year, conditions of the sailing area, waters, route.

3.8.10 Planning and tendering: rules, regulations, institutes

- ✓ Approvals for construction and operation (See-Berufsgenossenschaft, classification (GL, DNVL), EU machinery directive, etc.).
- ✓ BinSchO (inland navigation regulation).
- ✓ Shipping area (national/federal waterway zones, sea, inland waterway…).
- ✓ Legal questions concerning order and safety.
- ✓ State/federal environmental regulations, WasserhaushaltsG, noise and other emissions, BImSch.
- ✓ ZSUK (Ship Inspection Commission) Shipbuilding regulations.
- ✓ Designer, shipping company, shipyard.

3.8.11 Local interests and environmental relevance

- ✓ Environmental goals, climate policy of the local authority/corporation, CO2-neutral operation, e.g. by battery-powered ferry as a means of implementation.
- ✓ A battery electric ferry is a means of implementation.
- ✓ Relief and balancing of the means of transport.
- ✓ Concession award by the city/municipality.
- ✓ Integration into the local public transport system, multimodality.
- ✓ Transportation order/services of general interest.
- ✓ Taking along bicycles, prams etc..
- ✓ Tariffs and costs.
- ✓ Tourist use.

3.8.12 Local interests: Budget, financing

- ✓ Use dependencies on structural and local conditions.
- ✓ Investment volume for conversions and infrastructure.
- ✓ Taking into account the experience and wishes of the operator.
- ✓ Savings potentials: Weigh investment costs against operating costs in the long term.
- ✓ Budget, grants, subsidies.
- ✓ Fare and tariff structure (cost-covering or subsidized).

3.8.13 Municipal interests and sustainability

- ✓ Technical feasibility and safe operation.
- ✓ Economically sustainable; "no experiments".
- ✓ Long-term operating costs for the use of the vehicles and the infrastructure.
- ✓ Maintenance and servicing etc. and perspective maintenance costs.
- ✓ Strategic investment and operating cost planning, especially technological developments and trends that influence costs.
- ✓ Estimating and taking into account political and price developments.

4 Electric mobility on the water

4.1 Background, advantages and disadvantages

Electricity connections offer municipalities the following significant advantages and potentials for the implementation of their local measure dialogues (environment, infrastructure, economy):

- Electric ferries, especially all-electric ferries, do not cause emissions in operation and thus offer an effective measure at local level to support the implementation of the UNFCCC goals.
- low noise emission,
- no CO2 emission if energy source is CO2-free
- enable impulses for new tourist offers,
- create demand and jobs and generate added value,
- blend in and enrich the regional landscape,
- relieve the traffic network and decelerate regional traffic.

In order to achieve the above-mentioned advantages and potentials in their entirety, however, further research and development activities are still necessary. This concerns above all the drive, energy supply and energy management.

Fully electric ship concepts are based on different principles (e.g. lightweight construction) than traditional ships, if they are optimized for fully electric operation. Nevertheless, there is a need for retrofitting conventional ships and equipping them with electric propulsion systems. [31]

Accordingly, there is a need for research and development, ship design, equipment and operation in the following fields:

- Lightweight: design, construction and construction principles,
- Lightweight materials: composites, new and traditional materials,
- Hydrodynamics, ship shape, underwater hull, coating, textures,
- Shipbuilding principles, modular design,
- Functional outer skin surfaces and anti-fouling systems,
- Energy-saving equipment and energy systems,
- Automated driving, assistance systems, collision avoidance, navigation*,
- Automated Mooring & Charging,
- Remote maintenance and monitoring, maintenance, security concepts,
- Optimized energy management systems, driving profile, adaption to weather conditions, seasons,
- Operational improvements, traffic management, timetables and digital passenger information, standards, etc.

*For example, the funding project GALILEOnautic is developing solutions for autonomous shipping with the aim of increasing the degree of automation of all operating areas, creating driver assistance systems for ships with different types of propulsion.

A forward-looking project in this context is for example the "Neptun Hopper" of Neptun Ship Design GmbH. [31]

Figure 20 Neptun Hopper at the ferry terminal. [32]

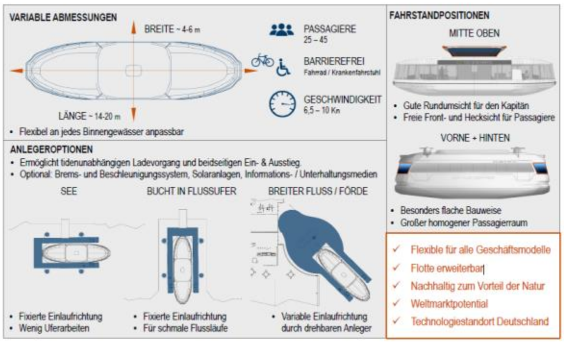


Figure 21 Neptun Hopper – selected functions. [31]

Advantages and disadvantages of electric ferries compared to conventional ferries

Electric mobility is the trend. Electric mobility is the future. But there are serious arguments for and against electric drives on ferries and passenger ships for urban water transport and on inland waterways.

The advantages are

- Very high efficiency of the drives: maximum torque already available at low speed, high acceleration possible. For small ferries and on short distances, full operation with solar energy is possible,
- Relatively simple drive train design: fewer moving parts, less maintenance, fewer repairs, longer service life of wearing parts,
- Very low operating costs: no fuel consumption in standby mode, lower energy costs,
- Environmentally friendly: very quiet operation and emission-free operation, no emissions during operation and idling, no soot particles, no carbon dioxide (CO2), no nitrogen oxides (NOX), no sulphur oxides (SOx),
- Tax advantages: financial incentives are still relatively high,
- Investment friendly: for moderate ranges not more expensive than conventional ships.

Disadvantages are

- In winter: no waste heat from the diesel engine can be used, an additional heating for passengers is required,
- Electric charging infrastructure or special infrastructure for hydrogen use must be set up,

It can be estimated that a significant part of the ships and ferries on inland waterways and coastal waters, passenger ferries, car ferries and passenger ships can be operated entirely by electric propulsion. [31]

4.2 Socio-economic and temporal classification of electric mobility

To classify mobility and especially electromobility, it makes sense to classify the development of electromobility technologies and their predecessors in socio-economic and temporal terms.

Mankind has known transport by means of machine-driven vehicles for about 150 years. Mobility as a mass phenomenon, as it is familiar to everyone today, has only been known to mankind for about 75 years. Before that there were the stagecoach, the horse-drawn carriage and the beginnings of the railway.

After the Second World War, the accelerated development of mobility, individual transport, electrical engineering/electronics, audio-visual media, information technology and other economic and technological fields had a strong influence on society. The generations living today have already consciously experienced several technological cycles that follow an exponential development.

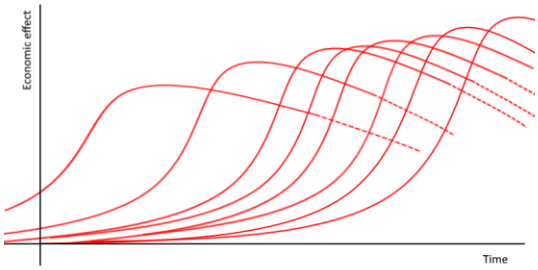


Figure 22 Technology life cycles. [33]

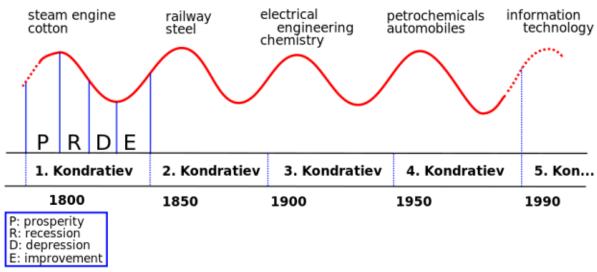


Figure 23 Kondratiew-cycles. [34]

Nikolai Kondratiev described this development and acceleration in a broader context through the so-called Kondratiev cycles, which represent the emergence of basic technologies over time as cyclical events, e.g. steam engine, railway, electricity, automobile and petrochemicals and information technology. Each wave of technology causes further technological developments, whereby these are accelerated, and the maxima follow each other in shorter time intervals. [34]

Table: Relationship and examples of the periodicity of the technosphere and biosphere in relation to transport and mobility

Technology	**Period of change**	**Extent of change**
Wagon/wheel	several thousand years	hardly
Carriage	several hundred years	hardly
Steam locomotive	several decades	running
Diesel locomotive	--„--	running
Electric locomotive	--„--	Running
High-speed train	--„--	Running
Automobile	several years	running, annually
Electromobility	several years	running, annually

The periodicity (time dimension) of technological developments shortens over time and takes an exponential course. The biological time of human life does not follow this acceleration. However, technogenic and bio-logical time influence each other and overlap. In the simplest and very individual example by the own experience of the waves of technology and information.

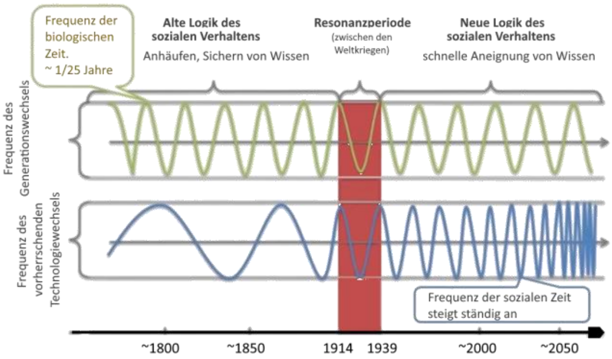


Figure 24 Change in the logic of social behaviour as a result of different times. [35]

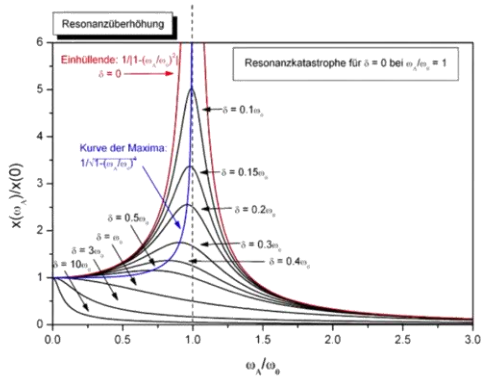


Figure 25 Resonance processes in relation to natural oscillation (Eigenschwingung) ω_0 [35]

Like all periodic processes in nature, music and technology, social developments and societies can also be regarded as oscillating systems with specific natural frequencies ω_0 (the very own frequency of a system). If an oscillatory system is excited from outside, in societies e.g. by information or serious events, a "system response" occurs. These can be resonance effects, for example.

Resonance processes occur when the frequency of the external excitation ω_A is equal to the natural frequency ω_0 of the system. With harmonic multiples, e.g. octaves ($\omega_A = 2\omega_0$), as well as other harmonic multiples, the amplitude is amplified. Such phenomena can express themselves for example in unrest, riots, conflicts and wars, which can be observed at present. (The question: What are the vibration- stimulating events?)

4.2.1 Urbanisation

In the past, statehood was concentrated in the cities. Cities are the states of tomorrow.

More and more people around the world live in cities, making them the most powerful actors and most important problem solvers in a globalized world. [36]

As economic performance continues to develop and the population grows, the trend towards urbanization continues worldwide.

The term urbanization (lat. Urbs = city) refers to the spread of urban lifestyles. This can be expressed in the growth of cities (physical urbanisation or "urbanisation") or through the infrastructural development and integration (functional urbanisation) of rural regions (suburbia) comparable to urban standards, as well as the changed social behaviour of the inhabitants (social urbanisation). In addition to physicial urbanisation, the expansion of cities through construction, trade and industry, urbanisation also includes the social change of urban lifestyles. [37]

Cities are more than just places; urbanisation involves more than the transformation of living spaces; it includes new forms of networking and mobility. Urbanization includes physical, functional, social and cultural dimensions and their transformation processes.

Large metropolises act like magnets. Istanbul is cited as an example in Europe. With a population of 14.3 million, it is one of the largest cities in the world. The high number of inhabitants poses great problems for the city, because the rural population prefers to move to Istanbul in search of work. As a result, the population density continues to rise, which creates immense problems for urban traffic. Delays in commuter travel times and air pollution are immediate consequences. [38]

This extreme example illustrates the link:

- Urbanisation as a social process is linked to mobility,
- Mobility and environmental protection are closely linked,
- Electric mobility in urban transport systems is a long-term necessity,
- Electromobility in its many variants influences the development of mobility behaviour and transport systems.

Trend towards urbanisation [39]

A trend towards urbanisation can be observed worldwide. Smaller units such as villages and small towns are growing together and forming densely populated areas. The increase in urbanisation and urban population can be structured as follows:

- The founding of new cities,
- Reclassification of settlements previously classified as "rural" (incorporation),
- natural growth of the urban population (excess of births),
- Migration movements (migration gains) from the country to the city.

In addition to the reasons mentioned above, the degree of urbanisation also depends on the structure, culture and history, the economy, the population size of a country, as well as geography and climatic conditions. In Germany, for example, the figure at the beginning of industrialisation was around 7% and is now 77% (2019). The following table and graph show the degree of urbanisation for different countries.

Table: Degree of urbanisation in selected countries, values: 2018, [40]

Denmark	87,9%	BSR
Sweden	87,4%	BSR
United Kingdom	83,4%	
United States	82,3%	
Norway	82,2%	BSR
Germany	77,3%	BSR
Turkey	75,1%	
Russia	74,4%	BSR
People's Republic of China	59,2%	
World average	**55,3%**	

BSR = Country oft he Baltic Sea Region.

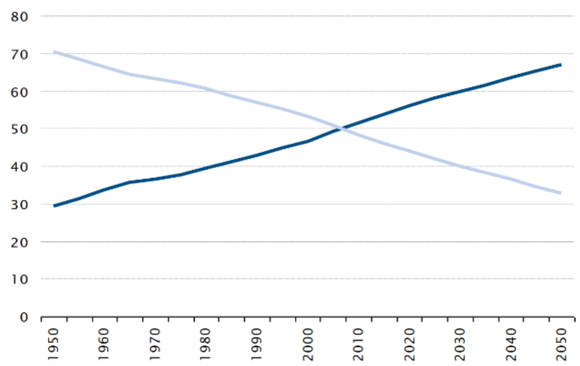


Figure 26 Worldwide percentage of urban and rural population. Curves, dark: urban, light: rural. [38]

Urban mobility, e-mobility and sharing economy

Sharing economy is seen today as an expression of a modern urban culture, where the principle of sharing and exchange is a basic human need. This principle is closely linked to the shared use of scarce goods and resources and to the division of labour. Economic goods that are in economic use are scarce by definition. In them, human labour is objectified for their production. Natural and economic resources have been and are traditionally managed in family associations and in local communities of participation. The oldest example is the "Theelacht zu Norden", a cooperative association that has administered and cultivated communal property for more than 1100 years (Battle of Norden in 884). [41]

The modern sharing economy is characterized above all by mobility, electric mobility and mobility-relevant contexts as an expression of urban culture. Thus, the "target groups" of the Sharing Economy can be found primarily in the milieu of the liberal intellectual and expedient strata, and the hotspots of the Sharing Economy are mainly metropolitan and urban areas. While urbanity was the concentration of productive forces and the resulting fusion of cultures, today the [capitalist] mode of production is being transformed into liberal variants such as the sharing economy, home office, etc.

The principle of sharing and exchange as a basic human need is transformed in the sharing economy into commerce, with consequences for urban planning, for rules of communal living, for business models and social control.

The well-known business models are based on young companies, which, with their innovation, speed and financial clout from mostly established financiers, initially fill niches and build up markets. While in the romantic early days, the sector was still socially committed, this sector is now a business with all the rules of the market. [42]

From an economic and ecological point of view, this is definitely beneficial to the urban environment. Studies show, for example, that one sharing car can compensate for more than ten individual cars. This saves resources, space in urban areas, materials, energy, etc.

With regard to production and innovation cycles in the automotive sector, there is a shift towards other than traditional customer groups (sharing companies, rental companies) with higher utilisation of fleets, professional maintenance and servicing of fleets, which are now subject to greater wear and tear due to increased use.

Mobility is becoming more individual in its use but more centralised at the level of ownership. We can now observe trends that have their models in information technology in the mobility sector and they are increasingly continuing in the area of industrial production:

- Service models - mobility as a service,

- License models - privileges of use instead of ownership,
- Professionalization - bus systems, automation, autonomous systems
- Decentralization - distributed systems, individually configured using information,
- Decentralization of working models - home office, work as an event, work as a life-style.

Sharing-Economy as a marketing label with the additional designation "i" (i-share) encourages further initiatives, up to euphoric fantasies on the stock exchanges. The "older" semesters still know such phenomena from the times of the New-Economy and the dot-com bubble. (compare: [42])

With regard to Car-Sharing, studies provide

- members are predominantly young, male and urban and
- two thirds of Car-Sharing members rarely or never use the service.
- Remarkable: Car-Sharing members from households with their own cars are in the majority. [43]

Table: Use of Car-Sharing in the population [43]

Age group	Share
30 – 39 years (<40)	7%
>50 years	<1%

Group	Share	Comment
<40 years	80%	
Men	4%	80% of users are male
Female	2%	
Households w/o cars	46%	10% Households w/o cars
Households w/ cars	54%	

Transformation to the information society

The transformation to the so-called information society is becoming increasingly noticeable today and is expressed in the urban mobility of recent history. Technical development has always tried to enhance the senses and abilities of the human being and to imitate nature: locomotion, muscle power, seeing, hearing, feeling, up to "thinking" and the weather etc. The inherent desire and drive are the possibility of control over things and nature.

Today, almost all areas are covered and the information age is all about networking everything. In society's perception, information is gaining more and more importance, which it always had in nature, but is now becoming the focus of attention. The primacy of idea (immaterial) over material becomes visible, which the "old" always knew.

Table: Transformation through technological change and social reflection

Transformation from ..		to ..	Reflection/Example
Ownership of an item	→	Possession/use of an item	Car-Sharing
Objective/material	→	Information about the objective	3D-printing: Data is more valuable because the object can be printed at any time.
Material	→	Nonmaterial	Physical presence at conferences versus online meetings
Manifested		Un-Manifested	Laws vs. Privileges, Permissions, Orders (Executive Orders)
Bound, solidified, condensed...		Solution, (detachment) possibility, opportunity, un-happened...	...
... etc.			

The inherent contradictions can be counterproductive in their effects:

- Desire for control requires centrality, implementation requires decentralized resources that must be controlled,
- Avoidance of bondage opens up opportunities, but requires permanent "flexibility" and can hinder development,
- Overcoming manifest, "rigid" laws can make processes more flexible and accelerate them, privileges or permissions can be quickly withdrawn again by means of regulations.

Although real life also knows extreme examples, it is to be hoped that clever and far-sighted common sense will prevail, and that e.g. smart electric mobility will not turn into non-mobility in the end.

4.2.2 Mobility and urban traffic in a chronological overview

An essential characteristic of urbanization is the high density of all areas of social activity. The urban transport system functions as a communicative element, effectively linking people, goods and information. Developed urban transport systems reflect the economic power of metropolises.

A characteristic of increasing urbanisation is the reaching of capacity limits of mobility infrastructures. In cities with the highest volume of traffic, such as London, Brussels or Warsaw, significant traffic congestion occurs during rush hours. Although electric mobility reduces noise and exhaust emissions, it does not solve the capacity problem. [44]

Growing traffic volumes are changing the mobility behavior of urban residents. Increasingly, public transport or bicycles are being used. The younger generation in the cities is leading the way. Using instead of owning determines the new flexible usage trend, which is developing into an urban mobile lifestyle.

Future-oriented mobility concepts enable smooth intermodality between different means of transport, such as tram, train, bicycle, car-sharing, bus, e-bike or ferry. The ubiquitous availability of information about transport modes is coming to the fore and digitalisation is becoming an important driver for new mobility strategies.

New mobility strategies have the potential to reduce traffic volumes through multimodal diversification of different transport modes, as well as spatial and temporal shifts.

- Temporal diversification by shifting working hours, home office and new forms of work.
- Spatial diversification through different means of transport, routes and ways.

- Networking of transport modes to individual multimodal timetables through applied information technology.

The changes in mobility structures can improve the quality of life in cities by making urban space no longer a parking area for vehicles, but shared space for everyone. Overall, this can lead to a reduction in the need for motorised individual mobility and to a greater professionalisation of urban transport.

The use of fossil fuels for propulsion systems in urban agglomerations will change in favour of electric mobility for reasons of technology availability, short distances and environmental protection. Electric drives for means of transport in urban traffic systems should be the first consideration in future procurement. In this sense, electric ferries in urban transport are also absolutely sensible.

4.2.2.1 Railway as a means of passenger transport

Track-guided wagons, as forerunners of the railway, were known since the Middle Ages for the transport of ore and overburden in the mines of Northern Europe. In [45] it is reported of wagons guided on wooden rails. To make work easier these carriages were moved on the rails by people and horses.

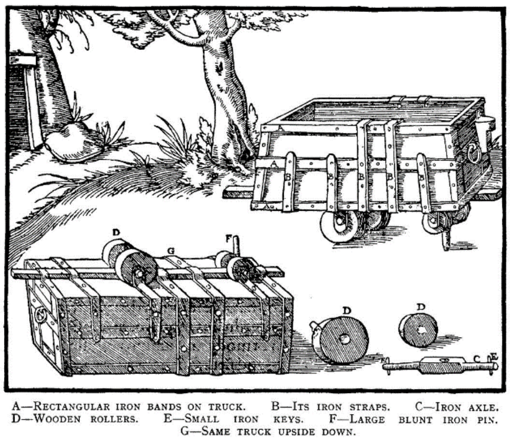


Figure 27 A wagon (hunt) guided on wooden rails in medieval mining. [46]

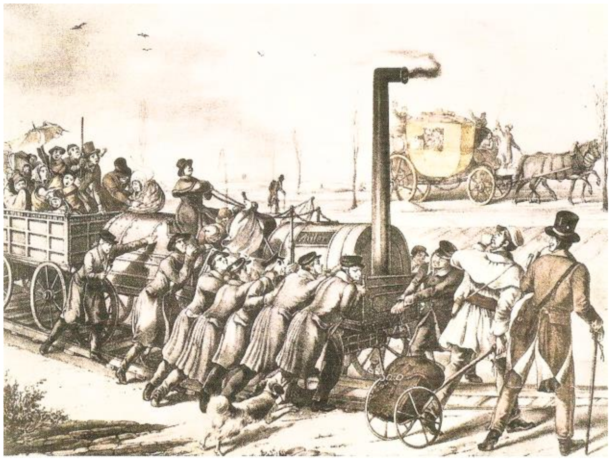


Figure 28 " Stagecoach against railway ", Satire from 1835. [47]

Since the middle of the 18th century, capacities have been greatly expanded. The greatest developmental leap was made by the railways with the introduction of mobile steam engines, which replaced the horse-drive. At this time, stationary steam engines were already in use in many industrially managed mines and manufactories.

The railway was not yet conceivable as a means of passenger transport; the dominant factor in the development of the railway was freight transport.

When the railway was introduced, it encountered a well-organized postal system that had reached a high level of organization and area coverage during its centuries-long development. Thus, investors in England could not imagine that the railway could compete with the well and cheaply functioning passenger mail on the English turnpikes (roads). A characteristic of the high degree of organization of the postal system was, among other things, the time management and statistics for the preparation of timetables and operation.

Despite scepticism, the history of passenger rail transport began in 1830 with the first railway line in England from Liverpool to Manchester, built primarily for passenger transport. [48]

With the industrial revolution, which began with the technology of the steam engine and the power industry in England, the English term 'rail-road' appeared around 1734. The engineer

William Murdoch, who worked for the company of James Watt, built a small mobile steam engine as a model in 1784. [49], [50]

In 1769 Nicholas Cugnot and later around 1801 and 1803 Richard Trevithick, succeeded in building "steam cars" that could travel on the road under their own power. Successful attempts to develop locomotives were made by Timothy Hackworth (1808), John Blenkinsop (1812), William Hedley (1813) and George Stephenson (mining locomotive 1814). On 27 September 1825, the locomotive "No. 1" built by Stephenson was the first in the world to transport people in public transport. Subsequently, the railway system developed in continental Europe and worldwide.

4.2.2.2 Electric battery, electric motor and precursor of electric ferries

The Italian physician Luigi Galvani (1780) noticed that a frog's leg, which came into contact with copper and iron, twitched repeatedly. He thought this was an electrical effect.

The first galvanic element (named after Galvani) was invented by Alessandro Volta in 1800 in the form of the Volta column. The Voltaic Column consists of many copper and zinc plates stacked on top of each other with pieces of electrolyte-soaked cardboard or leather in between. In the following years, design improvements were made and the development of a battery technology with the search for materials and improved constructions began. [51] [52]

As early as 1834 Moritz Hermann von Jacobi developed the first practical electric motor in Potsdam. On 13 September 1839, he installed a 220-watt DC motor with paddle wheels, which he had developed himself, in a rowing boat and tested the first electric watercraft on the waters of the Neva in St. Petersburg. The electrical energy came from galvanic elements with copper-zinc electrodes in the manner of a Voltaic column.

This was the first practical application of an electric motor and the first example of electric mobility. [53]

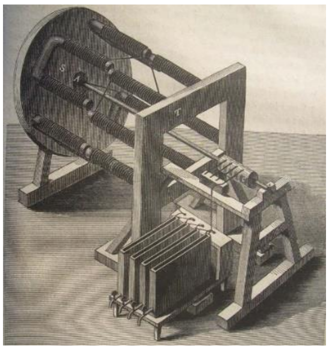


Figure 29 Electric motor by Jacobi around 1834. [53]

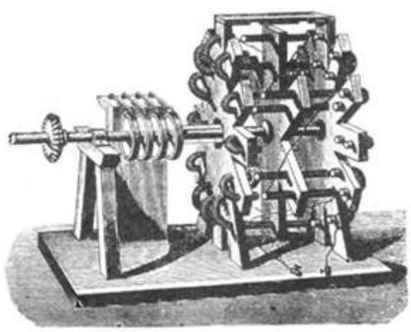


Figure 30 Improved Jacobi DC motor to drive the first electric boat in September 1839. [53]

In 1909, the first electric motorboat called "Accumulator" was used in Germany on Lake Königssee in the Bavarian mountain town of the same name. Since then, electrically powered boats have had a long tradition on the Bavarian lakes.

4.2.2.3 Electric trolleys and electric cars

Before the triumphal march of the petrol cars,
Berlin was the capital of electric cars.

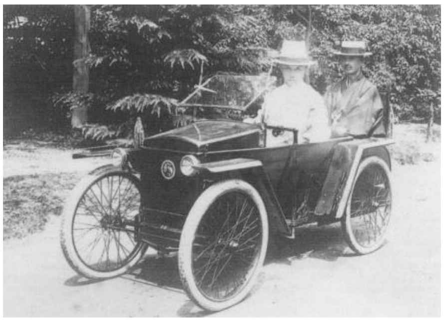


Figure 31 Dr. Slaby's electric car from 1920. [54]

Figure 32 In 1920, Berlin was the capital of e-cars. [55]

1832: Robert Anderson is said to have built an electric cart in Aberdeen. In November 1881 Gustave Trouvé presented an electric car at the International Electricity Fair in Paris [56].

In 1888 the flake electric car was presented (Auto-Presse.de, 2012). Coburger Maschinenfabrik A. Flocken is regarded as the world's first manufacturer of an electrically driven four-wheel drive car. From 1896 to 1939 there were around 565 brands of electric cars worldwide [57], [50].

60,000 battery-powered cars were on American roads around 1910. The vehicles could be recharged at many charging stations. After years of uncertainty as to whether gasoline engines or electric cars would prevail, almost 40 percent of cars in the USA ran on electricity, and the trend was rising. In 1912, almost 34,000 new electric cars were registered.

Despite the initial upswing, the decline of electric cars began around 1910 with the increasing availability of oil as a cheap fuel with a higher energy density. This made the more complicated internal combustion engine more profitable than the electric motor. The boom of the oil industry began. [58]

With the higher energy density, longer ranges are possible, which pushed the "highly sensitive batteries" to the sidelines. The electric motor remained in the car as a starter.

4.2.2.4 Electric trams

The world's first usable electric locomotive was presented by Siemens in 1879. The first electric tram was put into service in 1881 in Berlin-Lichterfelde after some resistance, after a concession for an electric elevated railway in Friedrichstrasse had failed due to resistance from local residents. Residents feared the devaluation of their homes.

In Rostock, for example, the tram was first put into operation as a horse-drawn tram on October 14, 1881. In 1904 the tram was electrified. [59]

Figure 33 Rostock tram 1881. [59]

Figure 34 Rostock tram 1961. [59]

Electric trams had their beginning with the development of the first electric locomotives and the opening of the first lines around 1881 in various cities. In urban agglomerations such as London, New York, Berlin, Paris, electric trams were subsequently opened.

The Berlin subway was opened in 1902 as the "Hoch- und Untergrundbahn" and had its technical lead with the electric trains from Siemens in 1881. Other German cities with subways followed in Hamburg in 1912, Munich in 1971 and Nuremberg in 1972. [60]

The New York Subway opened the first subway line on October 27, 1904 [61]. In London, the world's first tube railway (Tube), which was still pulled by a steam engine via cable, was opened on August 2, 1870 with the Tower Subway. The first electrically operated underground line was opened on 4 November 1890. The first subway line in Paris was opened on July 19, 1900 over a length of 10.3 kilometers. [60]

4.2.2.5 Internal combustion engines

It was not until 1876 that internal combustion engines followed as drives in mobility, later as electric motors. In 1876 Nicolaus August Otto developed a so-called flying piston engine, also known as an atmospheric engine, which was based on a Lenoir two-stroke gas engine patented in 1860. In 1864, together with Eugen Langen, he founded the world's first engine factory in Cologne.

On 27 February 1892, Rudolf Diesel applied for a patent for a "New Rational Thermal Engine" at the Imperial Patent Office in Berlin, for which he was granted a patent on 23 February 1893 under the number DRP 67207 with the subject "Working method and design type for internal combustion engines". The first car with an internal combustion engine was presented in 1886 by Carl Benz with his patented "Motor Car Number 1". [62], [63]

4.2.2.6 Oil as a driver of mobility

[50], [64]

Earth wax and crude oil was already known in prehistory. It was used, among other things, for sealing boats, as lubricating oil, as a remedy, as lamp oil. In Babylonia it was called "naptu", derived from "nabatu" = to shine, which is the origin of the Greek word naphtha for petroleum. Another term is petroleum = "stone oil", which was used to distinguish vegetable oil from animal fat.

At that time, whale oil was used as fuel for lamps, which became too expensive due to the decimated whale stocks. The idea was born to extract oil stored underground.

Figure 35 Standard Oil Refinery No. 1 in Cleveland, Ohio in 1889 (Paeger, Eine kleine Geschichte des Erdöls, 2006 – 2019)

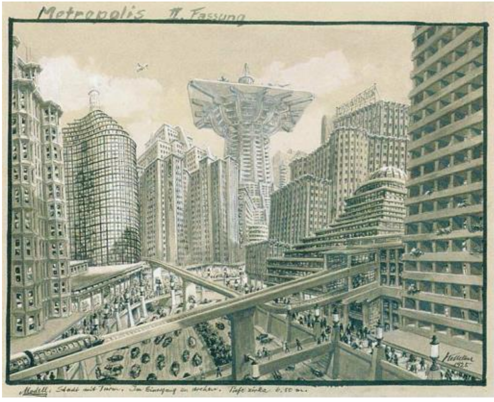


Figure 36 City and mobility of the future. Set design for the film "Metropolis". [65]

Its rise as the fuel of industrial society is closely linked to industrialisation and mobility. In 1865, the American Civil War came to an end. The rise of industrialisation, the development of the West and the wave of immigration from Europe created a huge market for oil. A young merchant named John D. Rockefeller recognized the potential in time. He started an oil trade and from then on took care of everything related to oil: from the cultivation of oak trees for oil barrels, to his own warehouses, marketing, export and safety standards. In 1870 he founded the Standard Oil Company and he became the richest man in the world.

With the onset of electrification (by Thomas A. Edison, incandescent lamp, among others), petroleum as lamp oil became a serious competitor but also a breakthrough. In 1882 the first power station was put into operation in New York. Standard Oil introduced the first oil stoves and oil burners for factories, trains and ships. Carl Benz' invention in 1886 marked the beginning of the age of motorised mobility and the creation of the largest market for oil. By 1900 there were already 9,000 cars registered in America. Twelve years later, the number had increased a hundredfold (900,000 registered cars) and by 1902, 17.5 million barrels of oil had already been produced, which led to the establishment of refineries to create Gulf Oil and the Texas Fuel Company (Texaco).

Railway construction and oil concession: In 1898, during a reception at the German embassy, Sultan Abdülhamid II presented the German Kaiser with an offer to Deutsche Bank for a concession to build a railway as far as Baghdad. Georg von Siemens decided to support the project, for which he was elevated to hereditary nobility for his "great services to the Ottoman railway system". In return, the Ottoman Empire ceded the mining rights for the oil and gas deposits, in a corridor of 20 km on each side of the railway line. On 5 March 1903, the final concession was granted for a period of 99 years. [64]

Mobility as a mass phenomenon is closely linked to socio-economic processes and developments, as well as to the development of the energy industry with petrochemistry as its most important pillar in the 20th century, and to technology and science. The power structures that emerged and consolidated in the process steered the world into a rapid development.

"You ask for what, not for how?

I wouldn't have to know shipping:
War, trade and piracy,
Triune are they, inseparable." [66]

4.3 Timeline on mobility and energy

1657	Rail-guided carriages in medieval mines as forerunners of the railways
1769	Steam carriage of Nicholas Cugnot
1780	Luigi Galvani discovers the galvanic element (copper/iron)
1800	Alessandro Volta invents the first electric battery (Voltaic column, copper/zinc)
1825	Locomotive "No. 1" by Stephenson. First passenger transport worldwide.
1834	Electric motor by Moritz Hermann von Jacobi in Potsdam
1839	First electric boat on the Neva, St. Petersburg
1859	Development of the first oil well in Titusville, PA (Pennsylvania Rock Oil Company)
1870	Foundation of the Standard Oil Company (Rockefeller)
1871	Discovery of oil near Baku on the Caspian Sea (Nobel Brothers)
1876	Development of the petrol engine.
1880	Exports of oil to Europe starts by the Nobel brothers
1880	The Rotschilds enter the oil business
1881	Electric car by Gustave Trouvé at the International Electricity Fair in Paris
1881	First electric tram from Siemens in Berlin
1881	The electric tram starts operation in Rostock
1888	Flocken-Automobil is introduced. First car factory for electric cars.
1892	Development of the "New rational heat engine".
1900	9,000 registered cars in America
1902	The "Hoch- und Untergrundbahn" opens in Berlin
1903	Concession of the Ottoman Empire for mining rights of oil and gas deposits in a 20 km strip along the Baghdad railway in favour of the German Empire.
1904	First electric subway line in New York
1907	Foundation of the Royal Dutch/Shell Group. Royal Dutch produced oil on Sumatra/Dutch East India
1908	Oil discoveries in Persia
1912	900,000 registered cars in America
1914	The British government secures 51 percent of the Anglo-Persian Oil Company (later BP - British Petrol Company)
1914	Start of the first world war (28 July 1914). Oil gains strategic importance.
1933	Standard Oil of California is granted a concession for oil exploration by Saudi Arabia. Foundation of the California-Arabian Standard Oil Co. 1944 Renamed Arabian-American Oil Company (ARAMCO)
1950th	Use of nuclear energy for large-scale electricity production.
2019	Wind turbines with a rated output of around 651 GW are installed worldwide.

4.4 Electric drive systems for Electric Ferries

4.4.1 Definition

A propulsion system consists of a source of mechanical energy or force and a propulsor (usually a propeller), which converts the mechanical energy or force into a propulsion energy or force and thus into motion.

Sources of mechanical energy or power are usually: internal combustion engines (diesel engine, gas turbine), steam engines, steam turbines, electric motors as well as combinations of internal combustion engines, steam engines or steam turbines with electric motors.

The following types of energy supply are relevant for the propulsion systems on electrically powered or hybrid ships:

- Internal combustion engines and steam turbines coupled with electric generators for the generation of electrical energy based on fossil fuels, such as heavy fuel oil, diesel, natural gas or liquid natural gas (LNG),
- Nuclear energy for steam turbines, coupled with electric generators,
- Electrical energy from batteries, in conjunction with a charging infrastructure,
- Electrical energy from fuel cells, which are powered by hydrogen,
- Hydrogen and CO2-neutral fuels for internal combustion engines used in steam turbines, coupled with electrical generators to produce electrical energy,
- Electrical energy from solar energy (photovoltaic) directly and temporarily stored in batteries.

The principle of an electric drive is shown in the following figure.

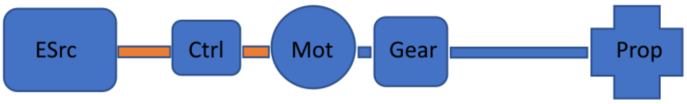


Figure 37 Principle of an electric drive. [67]

ESrc - electric power source, Ctrl – control unit, Mot - electric motor, Gear - gearbox, Prop - propeller.

For the principle of the electric drive described above, the following essential variants are relevant:

- Electric motor as DC motor: In the simplest case, the control system consists of a rectifier.
- Electric motor as asynchronous machine: The control is a complex frequency converter. Advantage: The asynchronous machine is relatively inexpensive.
- Electric motor as a synchronous machine: The control is a complex frequency converter. The advantage of the synchronous machine is a high-power density and a very good operating behaviour.

Depending on the version, the gearbox can be omitted in all variants.

4.4.2 Electric motor vs. heat engine

Simple design: A heat engine is much more complicated than a comparable electric motor. The electric motor can even be arranged outside the hull as a drive unit (see also below).

Low weight: An electric motor is considerably lighter than a heat engine.

Power performance/dynamics: Clear advantage for the electric motor. An electric motor is able to call up its full torque shortly after starting. A heat engine usually requires a certain speed to achieve maximum torque - to get as close as possible to this value during operation, the speed is adjusted via a gearbox. With an electric motor, a gearbox is not needed in many cases. The speed can be reversed with high dynamics without a gearbox. Accordingly, the maneuverability of an electric motor is much greater than with a heat engine.

Efficiency: At up to 95%, the efficiency of the electric motor is considerably higher than with a heat engine of maximum 55% for a diesel engine and maximum 65% for a gas and steam turbine arrangement.

Less noise: Electric motors are significantly quieter and generate less noise and vibration than heat engines. (An exception are steam engines).

4.4.3 State of the art

Electric propulsion has been used in shipping since the very beginning of motorization (see introduction). However, up to now it has only been used in certain applications, whereby the advantage of the electric motor is of particular importance. These are e.g. ships used for military purposes, icebreakers, research vessels, cruise ships. A major obstacle to the widespread use of electric propulsion systems is still the supply of electrical energy. The reasons for this are that at present, energy supply systems in mature industrial design are only available as internal combustion engines and steam turbines coupled with electric generators for the generation of electrical energy (gene sets) based on fossil fuels.

These drive systems in electrical energy supply systems have a lower efficiency than direct drives with internal combustion engines and steam turbines. In addition, the space required and the investment outlay are greater than for direct drives.

As an example of the use of electric propulsion systems, cruise ships with electric podded propulsion systems should be mentioned. On these ships, the electric traction motors are located underwater in a gondola that can be rotated through 360°. Comparable to an outboard motor, the pod drives act as rudders. The electric motors in the gondola directly drive the propellers. The electrical power supply is usually provided by a generator set using a diesel engine, gas turbine or steam turbine.

Figure 38 Two pods (Siemens Schottel Propulsor) for ferries. [68]

Figure 39 Azipod from ABB. [69]

CO_2-free energy supply systems for electric drives for large ships are at the beginning of their application. However, small ship units with battery systems or fuel cell systems are already in use. This will be discussed in the following sections.

The use of CO_2-neutral fuels for internal combustion engines and steam turbines will be discussed. At present, only the higher investment costs are considered to be an apparent disadvantage, because the consequences and costs of environmental and climate pollution cannot yet be sufficiently taken into account.

5 Energy supply for electric ferries

5.1 Battery systems

The structure of the battery system and the charger are shown in the following figure.

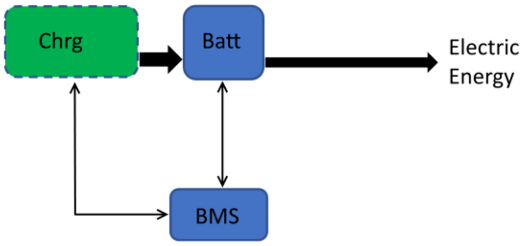


Figure 40 Structure of the battery system and charger. [70]

Chrg - charger, Batt - battery, BMS - battery management system.

The charger (Chrg) is usually positioned outside the battery system, e.g. as an electric filling station. The battery (Batt) is monitored by the battery management system (BMS) and controlled with regard to the energy output to the consumers. Furthermore, the BMS controls the charging regime of the charger depending on the condition of the battery.

5.1.1 Basic principles

The basic element of a battery is the galvanic cell.

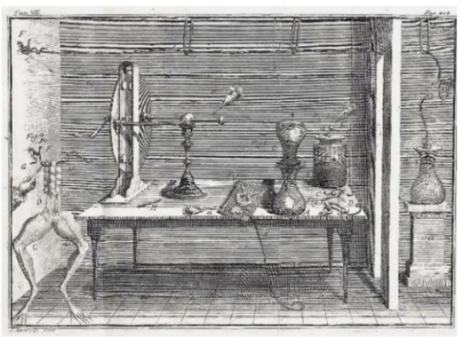


Figure 41 The experimental setup of the famous experiment (principle: galvanic cell) [71]

Figure 42 Volta column, principle: battery, here as a toy. [72]

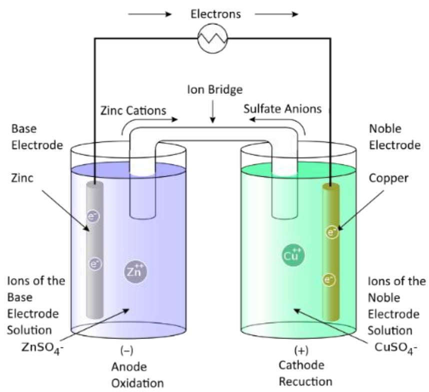


Figure 43 Structure of a galvanic cell. [73]

A galvanic cell or galvanic element is a device for converting chemical energy into electrical energy. Any combination of two different electrodes and an electrolyte is called a galvanic element and serves as a direct current source. The function of galvanic cells from a chemical point of view is based on a re-dox reaction, which is spatially separated in each half cell (half element).

The term galvanic cell goes back to Luigi Aloisio Galvani (1737 - 1798), an Italian doctor, anatomist and natural scientist. His fellow countryman Alessandro Giuseppe Antonio Anastasio Volta (1745 - 1827) is considered the inventor of the electric battery and one of the founders of the theory of electricity with the invention of the Volta column.

Galvanic cells use the electrochemical potential of the elements and the choice of materials for the anode and cathode is made accordingly. The electrochemical voltage series listed the chemical elements according to their electrode potential. It allows the calculation of the voltage of a galvanic cell as well as of batteries or accumulators, which is measured at the maximum when discharging or has to be applied when charging.

For example, the Volta column is made up of the elements copper (noble element) and zinc. The maximum voltage at one element of the column is 1.28 V = (Cu:+0.52V) - (Zn:-0.76V).

Table: Examples from the electromotive series:

Chem. Element	**oxidized Form**	**+ z e- ⇌**	**reduced Form**	**Standard-potential**
Copper (Cu)	Cu^{+}	+ e^{-} ⇌	Cu	**+0,52 V**
Copper (Cu)	Cu^{2+}	+ e^{-} ⇌	Cu^{+}	+0,16 V
Zinc (Zn)	Zn^{2+}	+ 2 e^{-} ⇌	Zn	**-0,76 V**
Lithium (Li)	Li^{+}	+ e^{-} ⇌	Li	-3,04 V

Table: Chemical reactions in batteries:

Entladen		**Laden**	
Anode	Cathode	Anode	Cathode
Oxidation	Reduction	Oxidation	Reduction
Minus	Plus	Plus	Minus
Electron emission	Electron uptake	Electron emission	Electron uptake
Elektrons	Protons		
Base electrode	Noble electrode		

Relevant terms concerning batteries and galvanic elements.

Anode	Pole at which oxidation takes place. Electrons are given off. If the anode and cathode are connected in a circuit, electrons flow to the cathode via the outer circuit. The anode acts as a negative pole.
Battery	Connection of individual primary or secondary cells (series connection) to achieve a desired total voltage. In fuel cells, the interconnection is called a stack.
Element	See cell
Cathode	pole where the reduction takes place. Electrons are absorbed.
Negative pole	See anode
Oxidation	Electrons are taken up by the molecules/atoms of the electrode.
Primary cells	These cells can be discharged once. The discharge is irreversible. Primary cells cannot be charged electrically. The commercially available carbon-zinc or alkaline batteries are primary cells.
Redox reaction	Combination (pair reaction) of reduction and oxidation as a simultaneous process. Oxidation: Substance A releases an electron as a reducing agent. Reduction: The electron is absorbed by oxidant B.
Reduction	Chemical partial reaction in which electrons are taken up by the molecules/atoms of the reactant (electrode material).
Secondary cells	Rechargeable cells, also called accumulator or collector. After discharge, secondary cells can be recharged. For this purpose, charge is collected and recharged against the direction of the discharge current. The chemical processes during charging and discharging are reversible within the cell. The number of cycles is limited by material and structure. The energy density of secondary cells is lower than that of primary cells at the same temperature.
Current (electric)	In electrical engineering, the direction of current flow refers to positive charge carriers. The direction of the current is opposite to the movement of the electrons. The current flows in a closed circuit (anode and cathode are connected): - in the outer part of the circuit from the cathode to the anode, - in the inner part of the circuit (in the component) from the anode to the cathode.
Cell	Galvanic cells are also called galvanic elements. Both terms are also used in connection with batteries.

5.1.2 Battery types

A basic distinction is made between primary and secondary batteries. The non-rechargeable batteries are primary batteries and the rechargeable batteries are called secondary batteries or accumulators. In e-mobility, only secondary batteries are used. For simplicity's sake, they are therefore referred to as batteries.

The following table gives an overview of the battery types and their gravimetric energy densities and charging efficiency. [74]

Batteriertyp	Energy density (Wh/kg)	Charging efficiency	Special feature
Lead	30	60–70 %	
Nickel-Iron	40	65–70 %	very insensitive to over- and deep-discharge
Nickel-Zinc	50	65 %	
Nickel-Hydrogen	60	75 %	
Nickel-Cadmium	40–60	70 %	Prohibited throughout the EU, with the exception of emergency systems and the medical sector
Lithium Titanate	70–90	90–95 %	fast rechargeable
Nickel-Metal Hydride	60–110	70 %	
Natrium-Nickel Chloride (Zebra-Batterie)	100–120	80–90 %	300 °C Operating temperature, no self-discharge, but heating losses 10-20 %
Lithium-Iron Phosphate	80–140	94 %	fast charging and high current capability, intrinsically safe
Silver-Zinc	65–210	83 %	expensive, short-lived, sensitive, very high capacitance
Lithium-Ion, based on LiCoO2	120–210	90 %	newer models fast charging capability
Natrium-Sulphur	120–220	70–85 %	300 °C Operating temperature, no self-discharge, but heating losses 15-30 %
Lithium-Polymer	140–260	90 %	practically any design possible
Lithium-Sulphur	350	90 %	laboratory prototypes
Aluminium-Ion	1000	n. a.	fast charging, experimental prototypes
Tin-Sulphur-Lithium	1100	n. a.	experimental prototypes

5.1.3 Essential characteristic values

In addition to the above mentioned parameters [74]

- gravimetric energy density,
- Charging efficiency,

the following are also relevant for the assessment of batteries:

- volumetric energy density,
- Self-discharge,
- Service life, cycle stability,
- Charging time,
- C-factor.

The main parameters for assessing and selecting the battery type are the energy densities. For the batteries currently under industrial control, Li-ion batteries have relatively high values for energy densities. In addition, the self-discharge characteristics, service life, cycle stability and charging time of Li-ion batteries are superior to those of other battery types.

5.1.3.1 The self-discharge

Self-discharge is < 2% per month at a temperature of 20 °C. The self-discharge is temperature-dependent. As the temperature rises, self-discharge increases.

5.1.3.2 The cycle stability

The cycle stability is a few 1,000 cycles. It depends on the state of charge and discharge and the dynamics of charging and discharging.

5.1.3.3 The service life

The service life of stationary batteries at a constant room temperature of 10-25 °C can only be achieved for traction batteries by thermal management. Unequal temperature fluctuations of the cells within the traction battery lead to differences in capacity and different ageing of the cells. The available capacity of a lithium battery decreases with falling operating temperature, especially below the 25 °C operating temperature at which the nominal capacity is determined, and should not fall below the freezing point of the electrolyte due to ice formation. On the other hand, the higher the operating temperature, the faster a cell ages, with a strong tendency to rise above approx. 40 °C.

The aim of thermal management is that at the same time all cells in the volume have the same temperature, which provides the highest possible performance with the least amount of ageing.

Furthermore, the BMS has a significant influence on the capacity of the cells connected in series, which is determined by the weakest cell during passive balancing. As a result, the total capacity is reduced, and the weakest cell is subjected to the greatest stress and ages the fastest. On the other hand, the complex active balancing can perform a charge equalization from the cells of high capacity to those of low capacity and keep the lifetime and the capacity of all cells available even for an older battery which is no longer homogeneous. Manufacturers offer a wide range of guarantees on the mileage of traction batteries according to their technology.

Practically speaking, charging times of 1.5 to 4 hours are common in the mobile device sector. Electric cars can recharge their batteries to 80 percent of their capacity at rapid charging stations (first built in 2017) within about 30 minutes.

The charging time of a battery depends on various factors. These include parameters such as the internal resistance, which has a direct influence on the charging current and is in turn influenced by temperature. Shorter charging times mean a higher current load and greater wear and tear, and are therefore in conflict with the battery's service life. Depending on the application, cell chemistry and technical implementation (air conditioning, monitoring), the practically achievable charging times therefore vary greatly.

5.1.3.4 The C-factor

The C-factor, also known as the C-rate [75], is a colloquial quantification for charging and discharging currents for batteries. It can be used, for example, to specify the maximum permissible charging and discharging currents, depending on the nominal capacity. The factor is also used to specify the battery capacity depending on the discharge current in the reverse case. The C-factor is defined as the quotient of the maximum discharge current Imax and the battery capacity C_N:

$$C = I_{max} / C_N$$

The C-factor indicates the reciprocal value of the time for which a battery of the specified capacity can be discharged with the maximum discharge current.

5.1.3.5 The capacity of a battery

The capacity of a battery at very high current draw is much smaller than at small currents. The charging voltage is determined by the cell chemistry and the battery structure. For this reason, there is an upper limit to the maximum charging capacity, which is reduced in favour of a longer service life. The practically achievable charging times are therefore usually higher than the technically possible charging times. External influencing factors are the temperature, the available voltage and current source and the charging method used.

The battery manufacturers specify the C-factors, the parameters to be observed and the utilization windows in data sheets.

5.1.4 Function of a lithium-ion battery

Lithium-ion batteries are increasingly used as energy storage on electric ferries. [76]

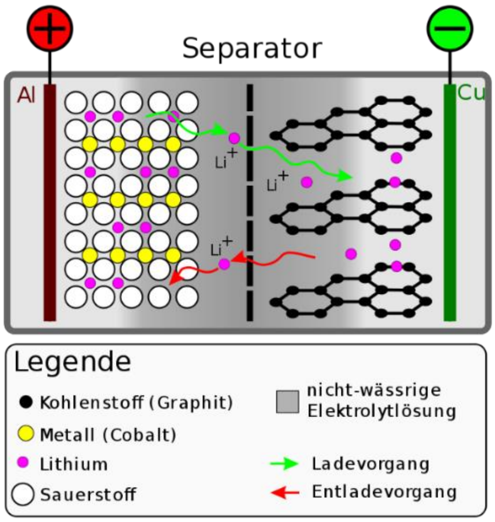


Figure 44 Schematic structure of a lithium ion cell (positive electrode: $LiCoO2$; negative electrode: Li graphite) [77]

Figure 45 View into the battery compartment of the M/F "Elektra". The lithium-ion battery has a total charge of 2 x 500 kWh. [78]

In the charged lithium-ion battery, the electrical potential difference of the electrodes is used to generate electricity in an electrochemical process with material change of the electrodes.

Lithium ions (Li^+) can migrate freely through the electrolyte between the two electrodes. In contrast to lithium ions, the transition metal and graphite structures of the electrodes are stationary and protected from direct contact by a separator. The mobility of the lithium ions is necessary to balance the external current flow during charging and discharging so that the electrodes themselves remain (largely) electrically neutral. The negative electrode is a graphite intercalation compound with the general composition Li_xC_n, with lithium as the cation. When discharging, the intercalation compound releases electrons which flow to the positive electrode via the external circuit. At the same time, the same number of Li^+ ions from the intercalation compound also migrate through the electrolyte to the positive electrode.

At the positive electrode, it is not the lithium ions that take up the electrons of the external circuit, but the structures of the transition metal compounds present there. Depending on the type of battery, these can be cobalt, nickel, manganese or iron ions, which change their charge. When the battery is discharged, the lithium is still present in the positive electrode in ion form.

Since the affinity of lithium ions for the material of the positive electrode is greater than their affinity for the negative (graphite) electrode, energy is released when lithium ions flow from the negative to the positive electrode.

Within both electrodes, electrons can move freely as an electron gas and migrate to the external conductors or enter the electrode from the conductors but cannot move between the electrodes within the battery. The partition wall is impermeable to electrons, which prevents a short circuit.

The figure above shows a lithium-ion battery configuration with an energy of 1 MWh on board the M/F "Elektra" (Turku, Finland).

5.1.5 Loading procedure

A variety of the following charging methods are known: [79]

- Constant current charging method,
- Pulse charging method,
- Reverse current charging or reflex charging,
- Constant voltage charging method,
- IU charging method (CCCV),
- IUoU charging procedure,
- IUIa charging procedure.

There are other charging methods which will not be discussed here, but only those relevant to lithium-ion batteries. In addition to the combination of constant current charging and constant voltage charging, these require the consideration of a deep discharge state at the beginning of the charge in which the battery cannot tolerate the full charging current. Because a deep discharge impairs the service life of lithium-ion batteries, this state of charge should be avoided. Adapted charge controllers therefore measure the open-circuit voltage at the beginning or increase the charge current up to the intended maximum value.

For maximum service life it is advisable to keep not only the depth of discharge but also the final charge voltage well below the maximum values specified by the manufacturer, i.e. close to the nominal voltage of the cell. The upper voltage limit of the cell should be avoided, as in this zone processes begin in the cells which irreversibly damage them and cause a reduction in capacity.

5.1.6 Problems and risks when using lithium-ion batteries

Fire hazard with lithium-ion batteries

The higher the energy density of batteries, the greater the risk of fire. Fires of lithium-containing cells develop differently from "normal" fires, such as those caused by leaking petrol. Meanwhile, extinguishing techniques and means of prevention are well advanced. [77]

The most common trigger for a fire is overheating of one or more cells. For example, in an accident between an electric car and a vehicle with an internal combustion engine, leaked fuel can catch fire and heat the battery. However, under certain circumstances, strong sunlight may be sufficient if the cooling system also fails. If the cell becomes too hot, the separator can melt - from around 150 °C - and an internal short circuit can occur. The cell that gets hotter and hotter as a result heats up the neighbouring cells, which can lead to thermal runaway of the entire battery system. This can result in temperatures of more than 600 °C.

However, overheating directly inside the battery is more likely, for example due to failure of the battery management system (BMS). Normally, the BMS protects the battery from harmful operating conditions. However, a defect in the electronics can lead to overcharging - with dangerous consequences. Equally destructive is an excessive current drain and even more so - if the fuse, which is usually installed, fails - a "hard" short circuit, in which several thousand amperes can flow.

But the other extreme also involves high risks. When charging a lithium-ion cell damaged by deep discharge, the lack of electrolyte fluid means that the amount of energy supplied can no longer be stored in the form of chemical energy, and the charging energy becomes heat. In addition, dissolved copper ions from the current collector are deposited on the graphite of the anode in the form of needles, also called dendrites. They can pierce the separator foil and cause a short circuit. [80]

Another cause of fire is mechanical damage to a cell - for example through an accident in an electric car, or after the end of use on the way to recycling [81] in the event of rough handling. Strict safety regulations must therefore be observed during collection. These are useless if consumers throw their mostly still functional and merely outdated mobile phones in the household waste. It has been reported that they have ended up in the paper bin and caused a smouldering fire in the paper press. [82] Intensive research is now being conducted to prevent such cases. Not only fires that started by themselves are the subject of meticulous investigations. Instead, intentionally generated fires are also being investigated under controlled conditions in a safe environment to study the individual processes and the success of various extinguishing methods. The tests performed in the test laboratories are deliberately made difficult.

Environmental impact

It is estimated that batteries account for about 15 percent of the total environmental impact of the manufacture, operation and disposal of an electric car (service life 150,000 kilometers). The greatest influence on the life cycle assessment, i.e. the greatest environmental impact, does not come from the battery itself, but from its proper use, e.g. regular charging and from the use of the power mix.

Multiple use of batteries and recycling can make batteries more environmentally friendly in the future. Cells that are too weak for mobile applications can be used in stationary energy storage systems. A large proportion of the raw materials from batteries can be recovered through recycling.

5.2 Fuel Cell Systems

The structure of the fuel cell system is shown in the following figure.

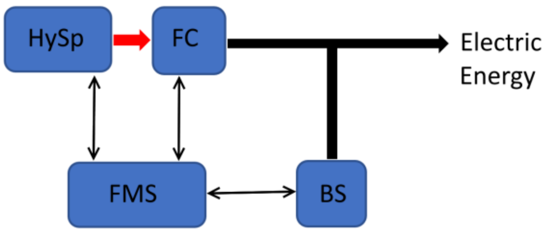


Figure 46 Structure of the fuel cell system. [83]

HySp - hydrogen supply (direct or indirect), FC - fuel cell, BS - battery system, FMS - fuel cell management system.

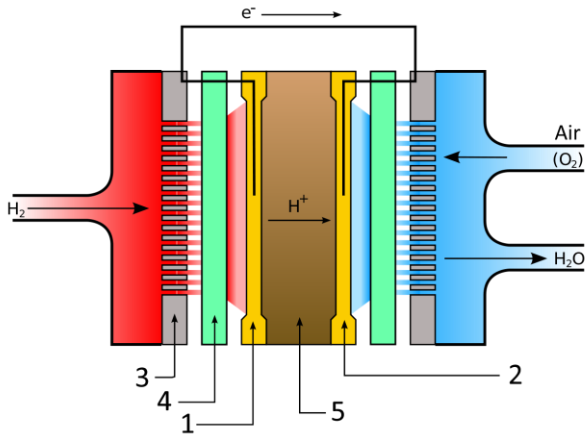


Figure 47 Structure of a fuel cell. [84]

1= anode, 2= cathode, 3= bipolar plate, 4= gas diffusion layer, 5= ion permeable membrane.

The hydrogen supply can be provided by a direct H2 supply, e.g. on the basis of compressed hydrogen, or by an indirect form, using chemical substances such as methanol. The fuel cell (FC) supplies electrical energy directly to the consumers and the battery system (BS). The battery system (BS) consists of the battery and an energy distribution system which is responsible for charging the battery or supplying electrical energy for the starting process of the fuel cell. The fuel cell management system (FCM) monitors and controls the hydrogen supply, the fuel cell and the energy distribution system of the battery system depending on the operating conditions. The size of the battery is dimensioned so that it can meet the maximum power requirement of the consumers, which is higher than the capacity of the fuel cell (FC).

5.2.1 Fuel Cells

Fuel cells are galvanic elements in which a redox reaction is used to generate electricity. Oxidation and reduction take place at the respective electrodes. The charge carriers are hydrogen ions (protons) in the fuel cell and electrons in the circuit. At the anode, the hydrogen molecule (H2) is divided into hydrogen ions (H+, protons) and electrons (e-). The hydrogen ions penetrate through the electrolyte to the cathode, while the electrons flow through an external circuit and generate electric current. Oxygen, usually from the air, is supplied to the cathode and combines with the electrons and hydrogen ions and oxidizes, ''burns'' to water.

The polymer electrolyte fuel cell (PEMFC) will be the main focus of this paper. It is the most advanced fuel cell.

The reactions at the electrodes are as follows:

Anode reaction:	$2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction:	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Complete FC reaction:	$2H_2 + O_2 \rightarrow 2H_2O + heat + electrical\ energy$
Energy conversion (kJ/mol):	$-\Delta H^0 = 286;\ -\Delta G^0 = 237$

The theoretical potential over all is +1.23 V (at 25 ° C):

$$E = \frac{237000\ (2\ mol\ H_2)}{96{,}493\ (4\ electrons)};\ E = 1{,}228\ V$$

In practice this voltage is not reached. Depending on temperature and operating mode, the voltages are between 0.5 and 1 V.

To obtain higher voltages, several cells are connected in series to form a fuel cell stack (see figure below). In theory, any higher voltage can be achieved in this way. However, there are limits to this due to cooling problems and flow losses during the supply of the reaction gases.

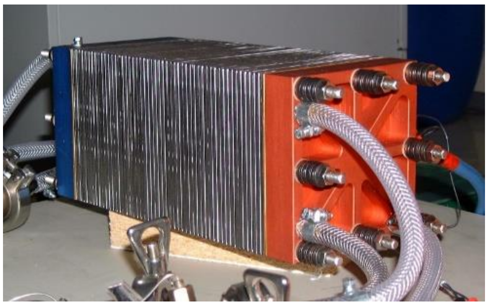


Figure 48 Fuel cell stack. [85]

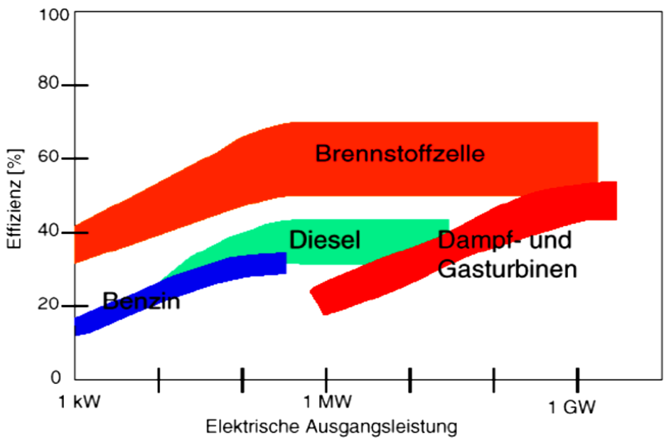
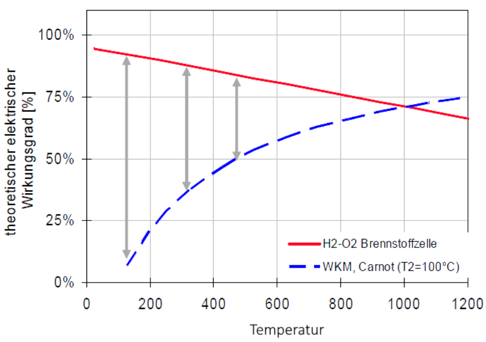


Figure 49 Comparison of efficiencies: FC with ICE. [86].

Furthermore, fuel cell systems require peripheral components for fuel supply, disposal and operation control. They are always operated together with a small battery, which is necessary for the on- and off-switching process. Furthermore, the battery relieves the fuel cell from power peaks in the consumer circuit and the fuel cell can thus be designed more favourably.



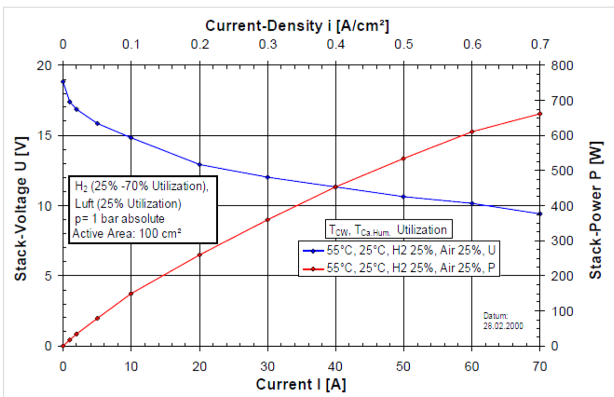


Figure 50 Comparison of efficiencies: FC with ICE. [86]. WKM= Wärmekraftmaschine.

Figure 51 Current-voltage power curves of a fuel cell stack with 20 cells. [86]

The main difference between a fuel cell (FC) and a heat engine (ICE) is that the efficiency of a fuel cell decreases with increasing temperature and that of a heat engine increases with increasing temperature.

A comparison of the efficiencies of different heat engines with the fuel cell shows that the FC is superior to the ICE at the current state of the art. However, developments are currently underway, especially for turbines, which allow a higher operating temperature and thus a higher efficiency.

The decisive operating behaviour of the fuel cell can be seen from the characteristic curves shown below. Conventional heat engines work more effectively at full load, with a greater drop in efficiency at partial load.

For fuel cells can be shown:

- as the current (load) increases, the voltage decreases and the power increases (non-linear),
- with increasing current, the efficiency of the fuel cell decreases (because of the proportionality to the fuel cell voltage).

This is where the great advantages of the fuel cell lie when used in vehicles.

The fuel cells are generally operated in a cell voltage range of 0.5 to 0.7 V. This corresponds to an overall efficiency of 40 % to 60 %. The overall efficiency takes into account not only the thermodynamic efficiency but also the voltage losses due to the chemical reactions and the energy for the peripheral components.

5.2.2 Fuel cell types

The differentiation of the types of fuel cells is characterized by different electrolytes, working temperatures and reactants (fuels). As a result of this, fuel cells have properties which in some cases differ greatly from one another. These qualify them for various applications.

Table: Types of fuel cells

System	Elektrolyte	Temperature	Fuel	Oxidizer	Catalyst
Alkaline Fuel Cell (AFC)	30% KOH	~ 80°C	Reines H2	Reines O2	Pt, Au, Pd, Ag
Direct methanol fuel cell (DMFC)	Sulf. PTFE	~ 80°C	CH3OH	Air	Pt, Ru
Polymer electrolyte fuel cells (PEMFC)	Sulf. PTFE	~ 80°C	H2	Air	Pt, Ru
Low temperature polymer electrolyte fuel cells (LT-PEMFC)	Sulf. PTFE	~ 80°C	H2	Air	Pt, Ru
High temperature polymer electrolyte fuel cells (HT-PEMFC)	Sulf. PTFE	120°C - 160°C	H2	Air	Pt, Ru
Phosphorsäurebrennstoffzelle (PAFC)	H3PO4 / SiC	160°C - 220°C	H2	Air	Pt
Molten Carbonate Fuel Cell (MCFC)	LixK2-xCO3 Li-AlO2	~ 650°C	H2, Erdgas	Air	NiCr, NiAl, NiO CoLiFeO2
Solid oxide fuel cell (SOFC)	ZrO4 / Y2O3	750°C - 1000°C	H2, Erdgas	Air	Ni/8YSZ, LSM

Special considerations on PEMFC and SOFC

The PEMFC and SOFC are the most commonly used fuel cells. The PEMFC is primarily used in mobile applications due to its high dynamics. The SOFC is primarily used in stationary applications because the high temperature level makes heat utilisation very easy.

Table: The main differences between PEMFC and SOFC

Criterion	PEMFC	SOFC
Elektrolyte	Polymer-Membrane	Solid ceramic electrolyte
Operating temperature	70 to 90 °C	650 to 1000 °C
Fuel	Hydrogen, natural gas, methanol, methane	Hydrogen, natural gas, methane
Application areas	Car drive, CHPUs, micro- Power stations	CHPUs, micro- Power stations
Elektrischer Wirkungsgrad	32 bis 37 %	33 bis 60 %

5.2.2.1 Solid oxide fuel cell (SOFC)

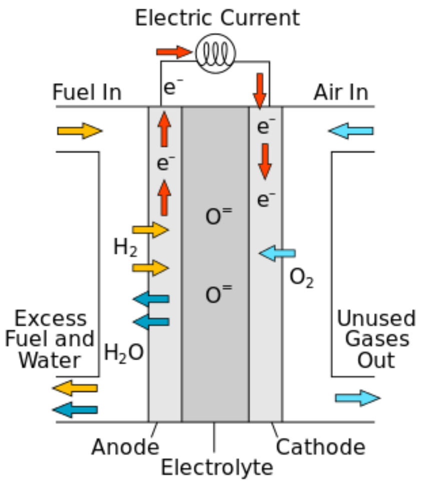


Figure 52 Electrochemical reactions on an SOFC. [87]

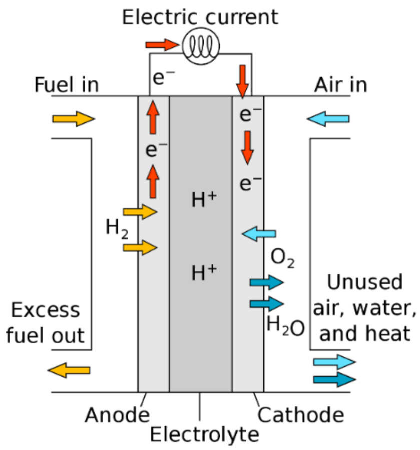


Figure 53 Electrochemical reactions on a PEMFC. [88], [89]

The electrolyte of the SOFC consists of a zirconium dioxide ceramic (solid electrolyte). Zirconia, which is obtained from silicate sands, has the properties of being heat and corrosion resistant even at very high temperatures. However, to be permeable to oxygen ions, zirconium dioxide requires external heating. It has an insulating effect on free electrons. Doping with yttrium enables good conductivity for oxygen ions at temperatures above 650 °C and increases the performance and durability of the membrane.

Due to the high working temperature of SOFCs (650 to 1000 °C), a reforming process for the preparation of hydrogen from alternative fuels (methane, natural gas, etc.) can be integrated into the cell. The high operating temperature is well suited for heat extraction (combined heat, power and cooling).

Like the electrolyte, the cathode is also a ceramic material (e.g. strontium-doped lanthanum manganate). The cathode and the anode are gas permeable and conductive.

Negatively charged particles, in this case O2 ions, migrate from the cathode side to the anode side. Thus, the process in the SOFC fuel cell runs in the opposite direction to the PEMFC fuel cells.

5.2.2.2 Polymer electrolyte fuel cells (PEMFC)

The main element of a PEM fuel cell is the membrane electrode assembly (MEA). A solid polymer membrane (thin plastic film) acts as the electrolyte in the fuel cell. If this polymer is saturated with water, it is permeable for protons, but does not conduct any electrons (electrical insulator). PEMs are mainly characterized by their proton conductivity (σ), their permeability (P) to the fuel and their thermal stability.

The electrodes are hot pressed onto the PEM. The material used for the electrodes is usually carbon fabric or carbon fibre paper. Required properties for electrodes are maximum gas permeability to the PEM and removal of water vapor from the PEM. The catalyst, a coating of carbon particles with precious metal impregnation, is applied to this carbon fabric (electrode).

The most commonly used catalysts for fuel cells are platinum and other metals of the platinum group. Ruthenium and platinum are often used together.

The high cost of these catalyst materials is still an obstacle to the economic acceptance of fuel cell technology. Research is therefore being conducted on alternative catalysts to reduce the proportion of precious metals.

A distinction is made between two types of PEMFC.

There is the **low temperature PEM fuel cell** (LT-PEMFC). It operates at lower temperatures. It is light and compact, which is ideal for mobile applications. However, it requires high-purity hydrogen with a CO content of < 10 ppm, otherwise the catalyst will be poisoned.

The **High temperature PEM fuel cell** (HT-PEMFC) operates between 100°C and 200 ° C. It has a higher tolerance to CO than the NT-PEMFC. It can therefore be operated with hydrogen, which has a CO content of approx. 1 %. However, the disadvantages are the lower dynamics and lower efficiency compared to the NT-PEMFC.

5.2.3 Load capacity and service life of fuel cells

Fuel cells for automotive applications have to meet tough requirements.

They must exhibit high safety, reliability, dynamics and high efficiency. The service life should be around ten years. So-called "Fuel Cell Dynamic Load Cycles" (FC-DLC) are used to investigate the trouble-free operation of fuel cells through dynamic loading, e.g. 73 dynamic load cycles of 20 minutes each per day. One load cycle simulates a driven distance of around 11 km, i.e. 512 cycles per week or 5621 km. The hydrogen consumption under full load was 7.8 kg per hour, which corresponds to 1450 normal litres per minute.

The test carried out at the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) examined a 100 kW fuel cell in continuous operation and achieved values corresponding to a weekly car mileage of more than 5600 km. [90]

A modified fuel cell of this power class would be quite suitable for the operation of an electric ferry.

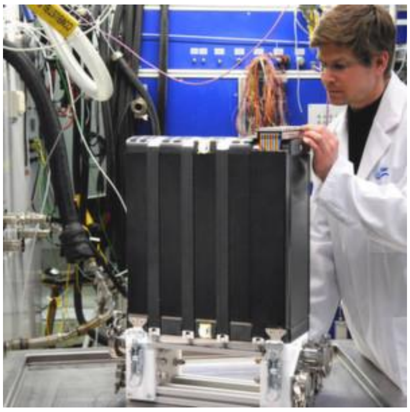


Figure 54 A 100-kW fuel cell stack on the fuel cell test stand at the Centre for Solar Energy and Hydrogen Research Ulm. [90]

5.3 Hydrogen supply

5.3.1 Direct hydrogen supply

Hydrogen is the most common of all elements in the universe. It is estimated that hydrogen makes up 75% of the mass of the entire universe. It is believed that 50% of the mass of the sun is hydrogen.

Pure hydrogen is relatively rare on planet Earth and it occurs almost exclusively in the form of chemical compounds.

Hydrogen is

- the lightest element,
- a colourless gas at 20°C,
- a colourless, clear liquid at -252 °C
- a crystalline solid at -259.2 °C,
- metallic at high pressure greater than 10^{11} Pascal.

Hydrogen technology and electric mobility are closely linked via the fuel cell. Hydrogen is of great importance as an energy carrier of the future with a view to harmonious interaction in harmony with nature, as can be seen from the following characteristics:

- Renewable energy - H_2 can be produced from renewable resources (e.g. wind, solar and water power).
- Efficient - H_2 fuel cell products are much more efficient than combustion engines
- Clean - H_2 is a carbon-free fuel.
- Safe - H_2 is safer than conventional hydrocarbon fuels.

At present there are still obstacles of a technical, technological and economic nature. However, despite the many open questions, technicians and experts largely agree that there is no way around hydrogen in the future.

Hydrogen production

For hydrogen production there are a variety of processes based on the use of hydrocarbons and biomass, and water splitting. Furthermore, the production of hydrogen as a by-product of industry is also of interest.

Table: Main hydrogen production processes (NHA, 2020)

Method	Process	Substance	Energy	CO2-Emission	Location
Thermal	Steam reform	Natural gas	High temperature steam	Yes	Centralised or decentralized
	Thermo-chemical water fraction	Water	High temperature heat from advanced gas-cooled nuclear reactors	Zero	Centralised
	Gasification	Coal and biomass	Steam and oxygen at high temperatures and pressures	Yes	Centralised
	Pyrolysis	Biomass	Moderate High temperature steam	Yes	Centralised
Electro-chemical	Electrolysis	Water	Electricity from wind, solar, water and nuclear power	Zero	Centralised or decentralized
	Electrolysis	Water	Electricity from coal or natural gas	Yes	Centralised or decentralized
	Photoelectric chemistry	Water	Direct solar radiation	Zero	Central
Biological	In the exploratory R&D phase				

The currently relevant H2 production processes, which can also be realized CO2-neutral, are water electrolysis and steam reforming of hydrocarbons.

5.3.1.1 *Water electrolysis*

Water electrolysis is the decomposition of water into hydrogen and oxygen with the help of an electric current. The reaction takes place in a vessel filled with conductive electrolytes (salts, acids, bases), which contains two electrodes that are operated with direct current. The principle of operation can be illustrated by the example of PEM electrolysis. Here the cathode and anode are made of polyellectrolyte material.

Table: Reactions at the water electrolysis

Anode reaction:	$H2O \rightarrow 0{,}5\ O_2 + 2\ H^+ + 2e^-$
Cathode reaction:	$2\ H^+ + 2e^- \rightarrow H_2$
Total reaction:	$H_2O \rightarrow H2 + 0{,}5\ O_2$
	Endothermic reaction
	reversible cell voltage: U= 1,23 V

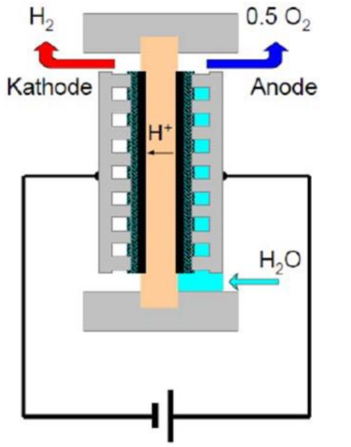


Figure 55 Functional principle of PEM electrolysis. [91]

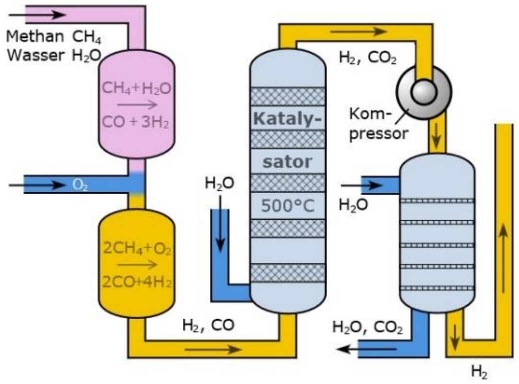


Figure 56 Principle process of steam reforming process.. [92]

Hydrogen production by electrolysis with the aid of electrical energy is regarded as the most important process for meeting the hydrogen demand in the future. Currently, there are two processes, alkaline electrolysis and PEM electrolysis. Both processes operate at comparatively low cell temperatures between 50 °C and 90 °C and can be operated both in centralized and decentralized electrolysis units.

5.3.1.2 Steam reforming

For the foreseeable future, fossil fuels will remain the most important source. The most economical method at present is steam reforming, in which natural gas and water react at high temperatures (700 - 1100 ° C) and in the presence of a metal-based catalyst (nickel). The starting materials for reforming are basically all hydrocarbons, such as natural gas, crude oil, methanol, etc.

Steam reforming is an endothermic reaction in which the required heat of reaction must be supplied. However, the heat can be supplied by simultaneous, partial oxidation of the hydrocarbons used. The efficiency (natural gas to hydrogen) is approx. 60 to 70 %.

Steam reforming is currently the most important process for the production of hydrogen on the basis of carbonaceous energy carriers and is used on an industrial scale. Approximately 95% of the annual world production of 500 billion m^3 is attributable to this process.

The reforming process is not only interesting on a large scale, but also works on a small scale. The most common hydrocarbon used is natural gas, but in principle light petrol, methanol or biogas, biomass and other fossil or recycled feedstocks are also suitable.

In addition to hydrogen, carbon dioxide and other exhaust gases are produced during steam reforming. Hydrogen is mainly used in the industrial synthesis of ammonia (artificial fertilizer) and for other chemicals.

5.3.1.3 Storage of hydrogen

For the direct storage of hydrogen, compressed gas storage, liquid gas storage and storage in metal hydrides as well as liquid organic hydrogen carriers can be considered. The gravimetric and volumetric storage density is the essential evaluation criterion of a storage system. Refuelling of the storage tanks is in the range of a few minutes. Especially the refuelling of a compressed gas storage can be done in a comparable time as e.g. a diesel refuelling.

Pressurised hydrogen storage

Here the hydrogen is stored in pressure vessels up to pressures of 700 bar. The energy required for compression is approx. 10 % of the hydrogen energy.

The storage of compressed hydrogen can be seen from two examples.

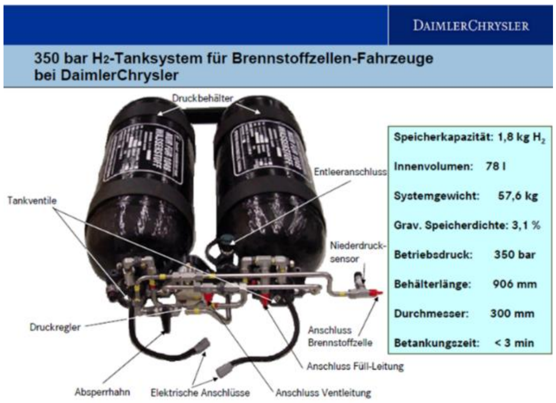


Figure 57 Pressurized hydrogen storage at 300 bar. [93]

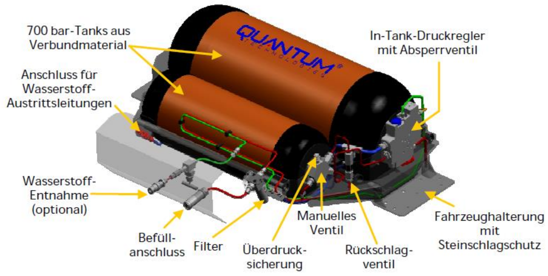


Figure 58 Pressurised hydrogen storage tank at 700 bar. [94]

The energy densities of hydrogen at 700 bar are

Gravimetric energy density	approx. 1.8 kWhH_2/kg total mass (H2+CFK pressure vessel)
Volumetric energy density	approx. 1.4 kWhH_2 energy/l pressure vessel

Liquid hydrogen storage

Here the hydrogen is stored at a temperature of - 253 °C. Accordingly, evaporation losses occur naturally. The energy required for liquefaction is about 30 % of the hydrogen energy.

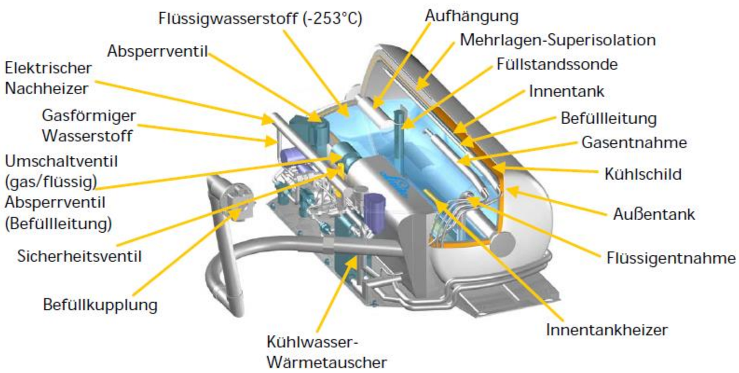


Figure 59 Liquid hydrogen storage. [95]

The energy densities of liquid hydrogen storage are

Gravimetric energy density	approx. 1.4 kWhH_2/kg total mass
Volumetric energy density	approx. 1.2 kWhH_2 energy/l container

Hydrogen storage by means of metal hydride and liquid organic water carriers

Here a chemical bonding of hydrogen takes place in which it is recovered as such and is not irreversibly converted into another fuel. The most important types are metal hydrides and liquid organic hydrogen carriers.

Metal hydride [96]

A time of 15 to 20 minutes at a pressure of > 10 bar is necessary for loading. The storage tanks have a relatively high safety level due to the low pressure level. When storing hydrogen in metal hydride, the following chemical absorption takes place:

- Metal + hydrogen → Metal hydride + heat

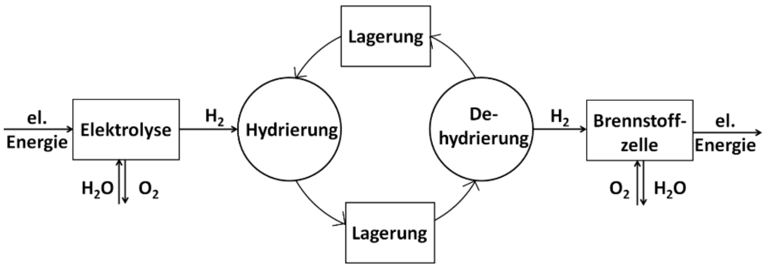
Figure 60 Metal hydride storage for hydrogen. [97]

The energy densities of hydrogen storage using metal hydride are

Gravimetric energy density	approx. 0.5 kWhH_2/kg total mass
Volumetric energy density	approx. 0.8 kWhH_2 energy/l container

Liquid organic hydrogen carrier [98]

As one form of indirect hydrogen supply, chemical reactions are used to bind hydrogen to substances as transport medium, which are not consumed themselves but are circulated, Liquid Organic Hydrogen Carriers (LOHC). These organic compounds take up hydrogen by chemical reaction and release it again. LOHCs can therefore be used as storage media for hydrogen.



Lagerung = Storage

Figure 61 Principle of indirect hydrogen storage via a chemical carrier. [99].

In principle, any unsaturated compound (organic molecules with C-C double or triple bonds) can absorb hydrogen during hydrogenation.

This storage process is still under development and is controversial because of the partly carcinogenic substances. Accordingly, this will be dealt with here only shortly afterwards.

To absorb hydrogen, the dehydrated form of the LOHC (an unsaturated, mostly aromatic compound) reacts with the hydrogen in a hydrogenation reaction. The hydrogenation is an exothermic reaction and is carried out at elevated pressures (approx. 30-50 bar) and temperatures of approx. 150-200 °C in the presence of a catalyst. The corresponding saturated compound is formed and can be stored or transported under ambient conditions. If the hydrogen is needed again, the now hydrogenated, hydrogen-rich form of the LOHC is dehydrated, whereby the hydrogen is released from the LOHC again. This reaction is endothermic and takes place at elevated temperatures (250-320 °C) again in the presence of a catalyst. Before the hydrogen is used, it may have to be purified from the LOHC steam. To increase efficiency, the heat contained in the hot material flow leaving the release unit should be transferred to the cold material flow of hydrogen-rich LOHC entering the release unit in order to keep the energy requirement for preheating the LOHC before the reaction low. Due to the relatively high temperature during dehydration, relevant losses of approx. 20 % to 30 % are expected.

The energy densities of hydrogen storage using liquid organic hydrogen carriers are estimated as follows:

Gravimetric energy density	approx. 1.7 $kWhH_2$/kg total mass
Volumetric energy density	approx. 1.8 $kWhH_2$ energy/l container

5.3.1.4 Refuelling infrastructure for compressed hydrogen storage

Currently, with a few exceptions, only refuelling infrastructures for compressed hydrogen storage are being developed and implemented worldwide. This is justified by the fact that compressed hydrogen storage has relatively low losses at usable energy densities and requires a moderate amount of equipment. Accordingly, only the refuelling infrastructures for compressed hydrogen storage will be discussed here. The refuelling infrastructure includes the transport of the hydrogen to the refuelling system and the refuelling itself. In some cases, even the hydrogen production takes place at the refuelling site.

In the following figures the different variants of the refuelling infrastructure are shown.

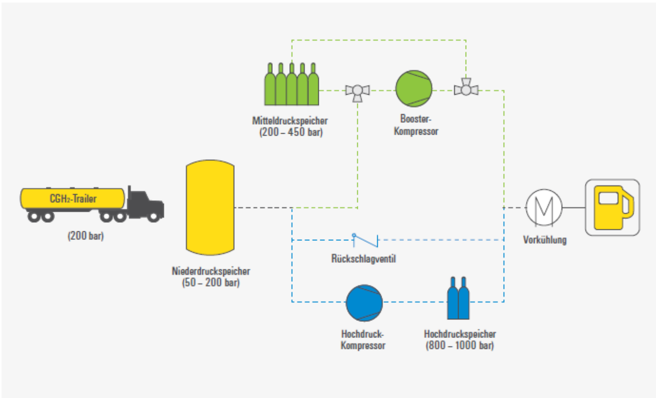


Figure 62 Refuelling infrastructure with gaseous delivery. [100]

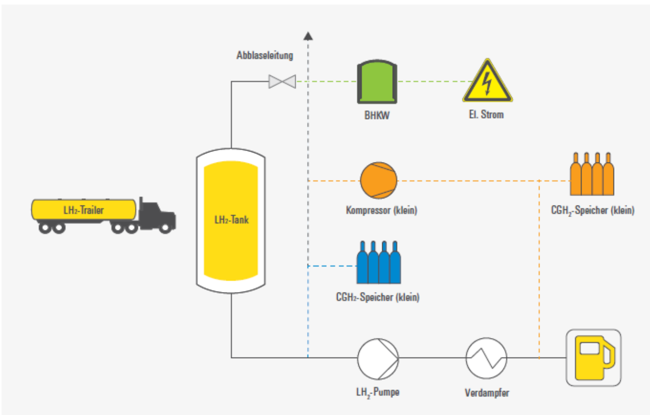


Figure 63 Refuelling infrastructure with liquid delivery. [100]

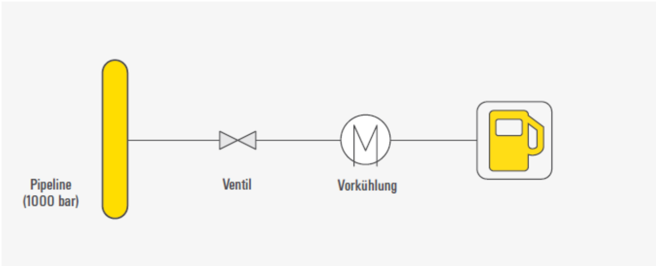


Figure 64 Refuelling infrastructure with high-pressure pipeline supply. [100]

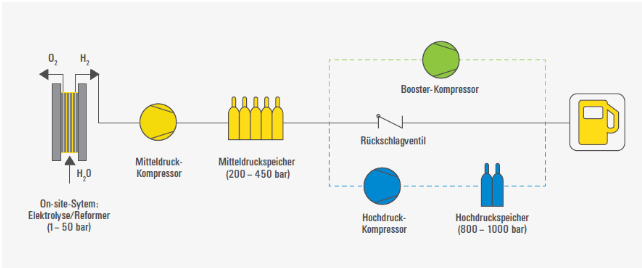


Figure 65 Refuelling infrastructure with on-site H2 production by electrolysis. [100]

An exemplary design of a refuelling system based on a liquid delivery is shown in the following figure.

Figure 66 Liquid hydrogen delivery at the Shell filling station in Berlin Sachsendamm. [101]

5.3.2 Indirect hydrogen supply

As has been shown in the previous section on refuelling infrastructure for compressed hydrogen storage, the cost of a direct hydrogen supply is considerable. Thus, the hydrogen supply of refuelling systems is relatively costly both in terms of implementation and from an energy point of view, e.g. for the transport of liquid hydrogen by pipeline. Furthermore, the pressure tank system must be equipped with a complex safety technology that requires frequent inspection. The acceptance of high-pressure hydrogen storage must also be viewed critically.

Formic acid, methanol and ammonia

The substances formic acid and methanol, in which the hydrogen is chemically bound, are particularly suitable.

Ammonia is also under discussion as an indirect hydrogen storage medium. The theoretical conditions seem to be quite favourable in the first consideration because of the relatively high gravimetric theoretical energy density of 5.9 WhH2/kg NH3. Ammonia is produced in the direct synthesis of hydrogen and nitrogen using the Haber-Bosch process. The gases nitrogen and hydrogen react with each other in a heterogeneous catalysis reaction in large reactors. Due to the necessary high pressure of several 100 bar and temperatures of about 500 °C, the production is very energy-intensive. Ammonia is also toxic and corrosive.

Formic acid and methanol can be produced by reacting hydrogen with CO or CO2. By means of reformation, a hydrogen-rich gas mixture can be produced from it again. This gas mixture contains considerable amounts of carbon monoxide or carbon dioxide. However, carbon monoxide in particular can cause problems when used in fuel cells.

At present, developments are underway for reforming and gas purification of formic acid and methanol with the aim of keeping the CO content below 10 ppm. This means that the effective NT-PEMFCs can then also be supplied with the hydrogen from the reformer processes.

The production of formic acid and methanol is to be carried out using CO2 from biogas plants and is therefore CO2 neutral. If sufficient CO2-free electrical energy is available, e.g. based on nuclear energy (fusion), CO2 from the atmosphere can also be used.

The theoretical energy densities of indirect hydrogen storage using formic acid are

Gravimetric energy density	approx. 1.4 kWhH_2/kg CH_2O_2
Volumetric energy density	approx. 1.7 kWhH_2-energy/l CH_2O_2

The theoretical energy densities of indirect hydrogen storage using methanol are

Gravimetric energy density	approx. 5.6 kWhH_2/kg CH_3OH
Volumetric energy density	approx. 4.4 kWhH_2-energy/l CH_3OH

Losses during reforming of formic acid and methanol and subsequent gas purification are expected to be 10 % to 20 %.

If the developments lead to the reformation of methanol to hydrogen with high purity (< 10 ppm CO) with reasonable equipment engineering effort, the use of methanol as hydrogen carrier for mobile applications can be considered very promising. This is also justified by the fact that methanol is comparable to the usual fossil fuels (petrol and diesel) in terms of handling. However, the toxic effect of methanol must be viewed critically. Accordingly, special measures are necessary for refuelling and storage. These are considered to be easily controllable with little effort. Nevertheless, developments and studies on safety are still pending, especially in the event of an accident situation.

5.4 Thermal engines for the generation of electrical energy with CO2-neutral fuels, hydrogen and nuclear energy

5.4.1 Principle of electric power generation with thermal engines

The principle of generating electrical energy by means of a heat engine (EWK) is shown in the following figure in a self-explanatory manner.

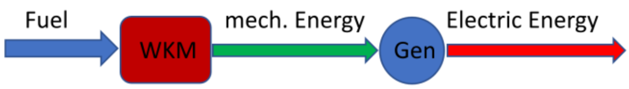


Figure 67 Principle of electrical energy generation using heat engines. [102]

WKM - heat engine, Gen - electric generator.

A heat engine is a machine that converts thermal energy into mechanical energy. In doing so, it exploits the tendency of heat to flow from areas with higher temperatures to areas with lower temperatures. The generation of heat results from redox reactions of chemical substances or from nuclear processes.

The heat energy is converted into mechanical energy by means of turbines or combustion engines, in this case rotational energy, and into electrical energy by means of an electric generator.

5.4.2 Essential evaluation parameters

Efficiency

The efficiency of a heat engine is derived from the Carnot process. This Carnot efficiency is calculated as follows:

$$\eta_{carnot} = \frac{T_{max} - T_{min}}{T_{\mathrm{m}}}$$

T_{max} – maximum combustion temperature,

T_{min} – min. temperature of the heat emitted by the heat engine (e.g. in the exhaust gas)

From this equation it can be seen that with increasing temperature difference the efficiency also increases. However, the practically achievable efficiency is smaller than the Carnot efficiency due to heat losses, friction losses etc.

Practical efficiencies, e.g. for large diesel engines, of a maximum of 55 % and for gas-steam turbine arrangements of a maximum of 65 % are achieved.

Electric generators achieve a maximum efficiency of 95 %. This results in maximum overall efficiencies for the generation of electric power by means of heat engines (EWK) of 52 % to 62 %.

Environmental pollution

Here, the pollutants sulphur dioxide and nitrogen oxides as well as carbon dioxide and methane are the main gases that are harmful to the climate.

5.4.3 State of the art and development trends for CO2 neutral fuels

In the automotive sector bioethanol is primarily used in petrol engines. In shipping, nuclear energy is used in steam turbines of warships and icebreakers.

The following fuels are under discussion or in development:

Hydrogen has been discussed as a fuel for thermal engines since the oil crises of the 1970s. There have been corresponding developments for gasoline engines, diesel engines and gas turbines. The principle feasibility was proven.

A major advantage of hydrogen is that it is CO2-free if it is produced from CO2-free sources (regenerative or nuclear energy). Furthermore, the pollutant sulphur dioxide is not present. Nitrogen oxides are, however, produced in contrast to the fuel cell.

5.4.3.1 E-Fuels

E-fuels are synthetic fuels that are produced from water and carbon dioxide using electrical energy. This process is called power-to-fuel and can be realized via power-to-gas or power-to-liquid technology, depending on whether gaseous or liquid fuels are synthesized.

In addition to the synthetic production of conventional fuels such as petrol and diesel, methane, methanol and ethanol are also being discussed.

The production is very energy-intensive and completely CO2-free. Here, the carbon dioxide is extracted from the atmosphere. The use of CO2 from biogas plants is energetically more favourable. In this case, however, only a CO2-neutral production of e-fuels is available. Nitrogen oxides are also produced during combustion.

5.4.3.2 BtL fuels

BtL fuels ("biomass-to-liquid", also known as synthetic biofuel) are produced from biomass. Bioethanol, biomethane and biodiesel are primarily produced. Methanol is also being discussed. Disadvantageous are, apart from the formation of sulphur dioxide as a pollutant (often in quantities compared to fossil fuels) and nitrogen oxides, the competition for food production on a large scale.

5.4.3.3 Nuclear fuel

The nuclear fuel can be used in currently existing nuclear power plants with an energy density of 1,056,084 kWh/kg. In contrast, the energy density of diesel is only 12 kWh/kg.

Diesel/ Fuel Oil	vs.	Nuclear fuel
12 kWh/kg		1,056,084 kWh/kg

The comparison shows that a nuclear power supply in the shipping industry allows for many new and advantageous utilisation concepts. However, the use of nuclear energy has some disadvantages. The main disadvantages are the release of radioactivity and the storage of spent, but still radioactive, nuclear fuel. Intensive international research is being conducted to eliminate these disadvantages.

One focus of research is nuclear transmutation. This is the transformation of a chemical element or an isotope into another chemical element.

The emerging transmutation technology aims to convert unstable isotopes (from nuclear waste) into nuclear substances with shorter and therefore more acceptable half-lives. [103]

Another focus is the development of nuclear reactor design of the IV. Generation. The development includes a sustainable closed fuel cycle for the reactor. For example, a molten salt reactor of the IV. Generation, a newly developed technology, has a high inherent safety [104]. The reactors operate at very high temperatures. This would, for example, allow high-temperature electrolysis for the highly efficient production of hydrogen.

5.4.4 Conclusion

There is currently no alternative to the generation of electrical energy by means of a heat engine for larger capacities, such as several megawatts for ocean-going ferries. Fuel cells are available with maximum outputs in the 100 kW range and their efficiency is also in the EWK range. With regard to the environmental and climate impact, hydrogen and nuclear energy should be used as fuel.

E-fuels should be viewed critically with regard to environmental pollution and the energy balance. BtL fuel is not the first choice in terms of competition for land for food production and environmental pollution.

Nuclear energy must be seen as very promising for the future, because it pollutes neither the environment nor the climate. The current safety and waste problems are being researched worldwide. Small nuclear power generation plants in the single-digit MW range are also under development.

5.5 Range Extender

A range extender is used to extend the range of an electrically operated means of transport whose energy supply is based on batteries. The function of the range extender corresponds to that of a battery charger, which is supplied with electrical energy from a fuel cell or a motor-generator set.

Serial hybrid drive

The use of an electric power generation system using a heat engine or fuel cell and battery charge control as range extender leads to a serial hybrid drive, a constellation in which the heat engine does not use the mechanical energy directly, but converts it first into electrical and then into mechanical energy.

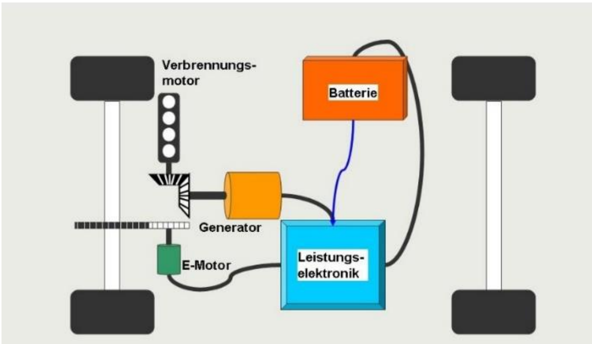


Figure 68 Range extender as a serial hybrid drive in an electric vehicle. [105]

Figure 69 Electric solar ship "Wolfsburg 2". The solar panels are the range extender here. [106]

The heat engine or fuel cell can be operated at the optimum operating point, so that the maximum possible efficiency can be achieved for this.

Ships with electric power supply based on batteries often carry a motor-generator set from which the batteries can be charged. Smaller electric ferries also use photovoltaic systems as range extenders, see example in the figure.

For selected sailing regimes, e.g. as ferries in inland waterways, with relatively low power and short distances, the batteries can be almost completely charged during the summer months via the photovoltaic system on board. The disadvantage, however, is that there is no free deck available, which is usually necessary for excursion ships.

For many applications, e.g. coastal and deep-sea cruises, a photovoltaic system is not practical because of the low power density of maximum 200 W/kW and the correspondingly high space requirements.

6 Electric ferries - Shipbuilding aspects

Referenced Literature a. o.: [107], [108], [109], [110], [111], [112], [113], [114].

6.1 Design and Shipbuilding Design of Electric Surface Vessels

The resistance of the hull is determined by the shape and speed of a ship. The superstructures of a ferry are usually compactly arranged. An influence of wind according to the respective environmental conditions must therefore also be taken into account. The resistance of a ship is composed of several components. These components include the frictional and form resistance of the hull, the wave resistance and possible wind influence according to the sailing area.

The propulsion system must overcome these resistances. The energy density of the accumulators of a ship's battery electric propulsion system defines the speed, the range and thus the cruise regime for the respective application.

For so-called displacer hull shapes, the Froude number is a measure of the ratio of inertial forces to gravitational forces within a hydrodynamic system. It thus evaluates the speed-length ratio of a displacer hull. With these hull shapes, the wave length and the wave height of the bow wave increase with increasing speed from rest. If the hull speed is exceeded, the resistance due to the bow wave increases for a ship in displacement mode. Various possibilities to reduce this hydrodynamic effect are used, for example by the arrangement of so-called bow bead attachments.

A displacement hull is unsuitable for purely electrically driven ships regardless of their size. Therefore, multi-hull configurations or so-called gliders or SWATH hulls with significantly better hydrodynamic resistance properties are developed. Besides the optimization of hydrodynamic properties, modern lightweight materials are still only used as material substitutes for mass reduction. There are only a few examples of a combination of the numerous elements to be considered in the development of an electrically driven ship.

6.1.1 Boundary conditions and potentials for the design and construction

The design of electric ships places completely new demands on the shapes of the hull and surface vessels. Traditional inland waterway vessels, such as push boats/push barges or river barges, are essentially not geared towards energy efficiency in drive and propulsion.

The development and construction stages must be coordinated with the local authorities (municipalities, STAUN, BUND, ...) as well as the supra-regional authorities (ZSUK, BWA, water protection agencies, BG Verkehr, ...) for the granting of operating licences, the guarantee of numerous guidelines or with the respective selected classification society accompanying the construction process.

Frequently, existing infrastructures or empirical values about the existing ferry traffic decide the size of the ship to be developed with further conditions like loading and unloading.

When establishing new ferry connections, corresponding preliminary investigations are necessary to determine such boundary conditions.

Small vessels as ferries and passenger ships represent a maximum degree of optimisation for their purpose. During the development process there are only a few possibilities to change essential characteristics or functionalities.

The use of lightweight construction materials often requires completely new approaches in many respects up to the actual production process.

The later use of the ferry or passenger ship in terms of functionality, operational profiles and acceptance by passengers is significantly influenced by this.

6.1.2 Optimization of the ship resistance depending on hull shapes and their ship design

The economic implementation of a fully electrified ferry concept or passenger ship operation is largely determined by the efficiency of the overall design of the ship. Hull, deck and superstructure, propulsion as well as functional installations or loading and unloading systems have to be optimised among each other.

The table shows hull shapes for small to medium-sized ferries and passenger ships as examples of possible hull designs.

Table: Hull shapes for small to medium-sized ferries and passenger ships

Displacer Hull

Classical hull forms based on previous designs for seagoing vessels are unsuitable for use in ferry traffic due to their special resistance properties. Also as a passenger ship, even at low cruising speeds, there is an inadequate ratio of the number of passengers to the required electrical power

Platform/Pontoon

This hull shape is also unsuitable for efficient use of electrically operated ferries, as is the case with the classic displacer. Nevertheless, this hull shape is often used for mixed traffic of passengers and cars/trucks on many rivers. The transport task requires a great variability in the carrying capacity. In addition, this hull form fulfils many landside infrastructural requirements due to the possible low draught.

Multihull/Catamaran

The catamaran or multihull (usually 3 individual hulls) is currently the most common hull de-sign variant for energy-efficient ship designs. The individual hulls are narrow with pointed bow shapes. They are connected by a platform structure similar to a bridge construction. This allows the wave resistance as well as the frictional and form resistance to be reduced. The variability of the carrying capacity is however limited by the displacement of the narrow hulls. It is therefore an important design criterion.

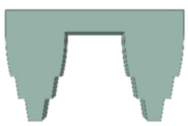
These hull shapes still allow a wide energy-efficient range of cruising speeds. They are also suitable for severe environmental and sea conditions. Catamarans are usually built from light-weight materials such as aluminium or fibre composites.

Glider Monohull

One-hull gliders are usually so-called 'deep V' structures. They have two cruise regimes. At low speeds up to 10 kn, the hydrodynamic behaviour is similar to that of a displacer. At higher speeds the vehicle changes to the glide mode.

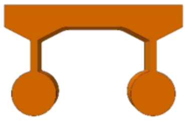
This hull form is often divided in the midship plane and then used as a catamaran hull in each case. From a hydrodynamic point of view, this variant generates a large proportion of bow wave resistance even at low speeds. It is less suitable for electric propulsion.

Glider Multihull



Maritime high-speed vessels are designed as multi-hull configurations. The individual hulls are often stepped in both longitudinal and transverse directions. This creates defined stall edges. From a hydrodynamic point of view, these are required to achieve the high sailing speeds. With an appropriate hydrodynamic design, the glide condition can already be achieved at speeds from 12-15 kn. A significant reduction of all resistance components is possible. These hull forms thus also show a high potential for purely electrically operated drive and propulsion solutions.

SWATH



Small Waterplane Area Twin Hull (SWATH) Double hulls with a small waterline area are ships with a special hull shape. The construction principle connects two torpedo-shaped underwater buoyancy bodies via narrow webs/supports with the platform arranged above the water. This hull shape is a special case of the catamaran structure. An advantage of this hull principle is the minimization of the wave resistance. Even strong swell can be compensated. These hull shapes also allow a wide energy-efficient range of cruising speed even in heavy environmental and swell conditions.

The variability of the carrying capacity is even more limited than in catamarans by the displacement of the narrow underwater buoyancy bodies. The load capacity according to the application is the most important design criterion. The draught can be changed by ballasting.

The underwater buoyancy bodies are predestined for electric propulsion and propulsion systems.

Hydrofoil supported hull shapes

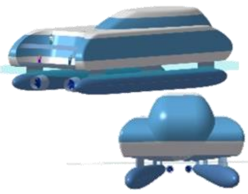
Hydrofoils are often used to minimize the resistance of glider (mono-, multi hull) hulls during the phase of displacement travel.

Hydrofoil supported hull forms are mainly used for maritime high-speed craft. The basis of such hull designs is often a fast glider.

The hull design for electrically operated ferries and passenger ships requires the optimisation of a multitude of factors relating to the respective transport task. In addition to the type of transport task, the infrastructural requirements, the cruise regime and the hydrodynamic requirements must be taken into account.

Hull designs from the field of displacers or pontoon shape represent the most unfavourable variants in terms of energy.

Table: Hull shapes for small to medium-sized ferries and passenger ships

Hull shape Suitability for **Accumulator/ fuel cell**	**Figure**	**Drive**	**Typical main data for ferries, inland and coastal shipping**	**Application profile**
Displacer unsuitable		Propeller, Pod drive Rudder propeller, Jet propulsion, Inline propulsor	LxBxT 50x10x3 m LoadCap. up to 1000 tdw 500-1000 kW; 150 nm 5-16 kn; 10 kn Passengers up to 350 Travel time appx. 90 min. Crew 5-7	ferry, inland passenger ship multiple ferry service
Platform/Pontoon conditionally suitable		Propeller, Rudder propeller	LxBxT 40x10x1,5 m LoadCap. up to 1000 tdw 500-700 kW; 50 nm 5-12 kn; 8 kn Passengers / cars up to 150/30 Travel time appx. 60 min. Crew 3-5	ferry, inland passenger ship
Multihull/Catamaran suitable		Propeller Pod drive Rudder propeller, Jet propulsion, Inline propulsor	LxBxD 50x10x1,5 m LoadCap. up to 1500 tdw 500-800 kW; 500 nm 5-16 kn; 12 kn Passengers up to 350 Travel time appx. 120 min. Crew 7-10	ferry, inland passenger ship
Glider Monohull suitable		Surface-Propeller, supercavitating Propeller Jet propulsion	LxBxD 20x8x1,5 m LoadCap. Up to 500 tdw 300-500 kW; 50 nm 5-20 kn; 15 kn Passengers up to 350 Travel time appx. 60 min. Crew 3-5	ferry, inland passenger ship
Glider Multihull suitable		Surface-Propeller, supercavitating Propeller Jet propulsion, Inline propulsor	LxBxD 40x10x1,5 m LoadCap. Up to 1000 tdw 1200 kW; 100 nm 10-25 kn; 20 kn Passengers up to 350 Travel time appx. 60 min. Crew 5-7	ferry, inland passenger ship
SWATH suitable		Propeller Pod drive Rudder propeller, Jet propulsion, Inline propulsor	LxBxD 50x10x3 m LoadCap. Up to 1500 tdw 500-800 kW; 250 nm 5-20 kn; 12 kn Passengers / carsup to 350/30 Travel time appx. 60 min. Crew 5-7	ferry, inland passenger ship
Hydrofoil-supported hull forms suitable		Surface-Propeller, supercavitating Propeller Jet propulsion, Inline propulsor, jacketed air propeller	LxBxD 30x10x2 m LoadCap. Up to 800 tdw 300-500 kW; 150 nm 10-30 kn; 20 kn Passengers up to 200 Travel time appx. 60 min. Crew 3-5	ferry, inland passenger ship

6.1.3 Influence of deck and ship shapes on propulsion power

The superstructures of ferries and passenger ships are designed according to their intended use. In the case of ferries, decks for passengers and cars or trucks and trailers dominate. Small passenger ships are connected by passenger decks and are characterised by panorama or sun decks. Generously arranged areas in the shipbuilding design can become wind-exposed areas. They act like sails and can also cause great wind resistance on inland waterways.

Bridges and other infrastructural obstacles can also significantly influence the shape and structure of deck superstructures.

The arrangement of solar cells to support the accumulator charge can also be a decisive criterion in deck design.

When designing the superstructure, the interactions between the ship's silhouette and the electrical propulsion reserves resulting from the resistance of wind and speed must always be taken into account.

6.2 Hydrodynamic parameters for the design of electric surface vessels

The most important indicators for the hull development are the necessary displacement, the cruising and service speed, the draught, the regional environmental and sea conditions as well as the route.

6.2.1 Load capacity, service speed, draught, manoeuvring and shallow water conditions

The main frame cross-sections shown schematically in the figure show the different possibilities of the respective hull shape to optimize the load capacity. The hull shapes catamaran and multi-hull glider allow a variable adjustment of the displacement to the transport task. A 'Deep-V'-catamaran as well as SWATH are hull shapes which are tailored to a defined displacement.

Important parameters for minimising the drag and thus optimising the required lower propulsion power are the hull shape, the waterline length, the waterline area, the wetted surface, the wave entry angles at the bow, the hull spacing and the stern design.

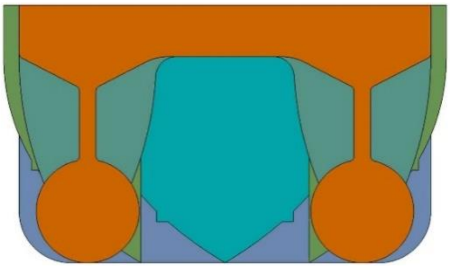


Figure 70 Schematic comparison of the main bulkhead cross-sections of the hull shapes described with regard to their arrangement and displacement (seen from astern).

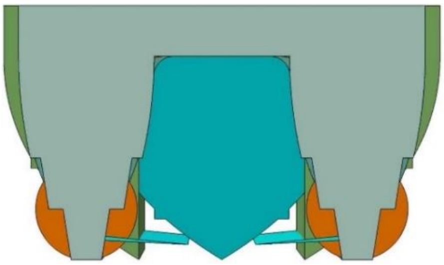


Figure 71 Schematic comparison (seen from the front).

The hull spacing in catamarans, for example, has a significant influence on wave interference from waves passing between the hulls. Even small wave heights on rivers and lakes have a significant influence, especially on small vessels.

The service speed of the vessel is another parameter determining the hull design. The service speed has a quadratic proportion with respect to the ship's distance. On rivers and inland waterways there are usually speed limits between 6-10 kn. These limits are set to protect the banks due to the impact of the waves. Even at these low speeds, hull optimisation is clearly noticeable in terms of primary energy consumption.

The manoeuvring behaviour in the area of the respective ferry or pier must also be taken into account. Depending on the local conditions, longer manoeuvres can occur in the partial load range of the drive and propulsion system. In this case the most favourable variant of the hull shape would be a catamaran or SWATH.

The draught is usually a decisive factor for the hull design, analogous to the deadweight tonnage. The conditions of the river or lake shore, combined with shallow water inflows and in connection with the respective jetty infrastructure, can, for example, lead to the decision for a pontoon shape when configuring a double-ended ferry with catamaran hull because of the pier ramp.

6.2.2 Sea state and environmental conditions on lakes, rivers and coastal waters

Sea state and environmental conditions on lakes, rivers and coastal waters differ from sea conditions on seas and oceans. As a rule, their effects are much smaller. Due to the increasing influence of global climate change, extreme conditions such as heavy rain, gusts of wind up to 60 m/s or special wind events such as tornadoes or waterspouts can occur locally. For this reason, wind-exposure areas in the above-water area must be designed in such a way that wind influences are minimised. This in turn has an influence on the design of the upper deck for possible solar cells to be arranged. The current state of the art for flexible solar cells in combination with fibre composites allows very good structural solutions that meet the requirements.

The influence of waves is not to be neglected on larger lakes or in river estuaries. In accordance with the standards and the definition of coastal, inland and sea areas, these factors must be taken into account in the hull or entire ship design.

6.2.3 Design and functional tasks of the surface vessel

The functional tasks of the surface vessel, decks and superstructure design for ferries are connected with the respective ferry task. In addition to providing the areas and rooms for the transport task, they serve to accommodate the batteries and drive technology. In many cases there is not enough space in the hull design for their arrangement.

The design of the superstructures usually determines the respective identification with the shipping company of the ferry line or passenger ship, the standard of passenger comfort and the catering facilities on board.

The access routes for the passengers are subject to requirements of the classifications such as openings on deck. These requirements serve, among other things, leakage stability and capsize safety. They are not specific for electrically powered ships.

The requirements for barrier-free access are a special feature. This has a further decisive influence in the totality of the parameters and characteristics to be taken into account for the hull design. In this context a SWATH hull design is to be emphasized. This fuselage shape shows only small fluctuation movements in waves at the jetty as well as during sailing.

A further special feature of purely electrically operated propulsion systems is the use of supporting solar cells to charge the battery during the journey. Here, not only the possible area exposed to the wind must be taken into account. The mass of the solar cells brought to the 'highest' point of the ship has a negative influence on the metacentric height of the ship and thus on the hydrostatic stability behaviour.

The design of the superstructure is often subject to technologically simple and cost-effective variants. Sophisticated design variants, some of which are futuristic, do not always represent the technically optimal solution either.

Figure 72 "Aluna" solar ferry. [115]

Figure 73 Electric ferry with solar panels. [115]

The design of the ferry "Aluna" is not optimal in terms of hull design with regard to the bow wave system that occurs during navigation. The superstructure design offers large wind attack surfaces of the front and side windows.

The electric/solar ferry of the Ostseestaal GmbH, on the other hand, is, despite the pontoon hull, much more effectively designed to minimize wind resistance. This is complemented by an attractive modern design which integrates additional solar panels.

The electric passenger ship "Future of The Fjords" was developed with an energetically optimized catamaran hull design. In the futuristic arrangement of the platform connection of the hulls and the design of the superstructure, the configuration was more in line with the design and not with the optimisation for wind susceptibility and rough sea conditions. In the northern latitudes, environmental conditions such as snowfall and icing have to be taken into account.

Figure 74 Electric passenger ship "Future of The Fjords". [116]

Figure 75 Electric passenger ship "Future of The Fjords". [117]

6.3 Propulsion and propulsion units for electric ferries and passenger ships

The design and layout of the propulsion systems and organs of ferries and passenger ships with electric propulsion is directly related to the overall ship design. The challenge, especially for small ships, is the necessary sophisticated system design. In addition to the technical parameters and boundary conditions, the availability of suppliers of high-quality, proven technology (engines, solar and battery technology, control electronics, fuel cells, etc.) is an important criterion.

6.3.1 Requirements and specifications of propulsion / propulsion for small to medium sized ferries and passenger ships

Due to their compact design, electric drives can be used in a wide range of speed and performance in a variety of designs. Technical standard solutions offer efficiencies of up to 95% and power weights of up to 26 kW/kg (e.g. Plettenberg Elektromotoren GmbH).

This allows axis-driven propulsors (propellers, trusters, pump radiators) to be positioned on hydrodynamically efficient hull areas. Smaller ship units require innovative solutions, e.g. for catamaran hulls with low constructional freedom.

The development of multi-pole brushless electric motors in combination with planetary gears and low-loss, vibration-free couplings in a power range of up to 500 kW enables completely new drive concepts for purely electrically powered vessels.

Under these conditions, the necessary accumulator capacities can be optimized in terms of storage capacity, mass, electrical control units for voltage and current management during charge/discharge, and frequency converters for the drive motors. Supporting solar cells become significantly more efficient in their application scenario. Small ferries or passenger ships for rivers and lakes in a size range of LoA 10-20 m become economically attractive. For this type of vessels, two times 30-50 kW propulsion power are usually sufficient for most applications with an innovative hull design. The mass and construction volume of the drives can be reduced by up to 30% and more. The payload or the accumulator capacity can be increased to extend the driving profile.

6.3.2 Specific characteristics for electrically driven propulsors

The speed, torque and power characteristics of diesel engines and electric motors differ significantly. With electric motors, the torque is already fully available at low speeds. The efficiency shows a distinct plateau. The torque and power curve over speed behaves analogously to the torque and thrust coefficients of propellers (see following figures). Thus, a propeller can be more efficiently adapted in its pitch or hydrodynamic propeller blade load for the power conversion into thrust. This results in new innovative possibilities for blade design. Contrarotating propellers are mechanically easier to design. Cross currents in rudder propellers as a result of jet deflection at azimuth rotations can be compensated.

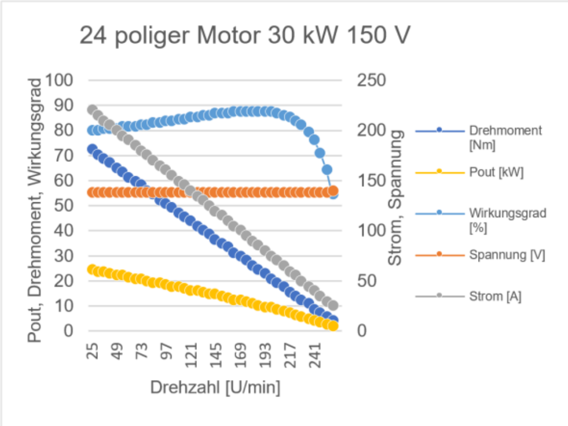


Figure 76 Characteristic curve of electric boat drive up to 30 kW

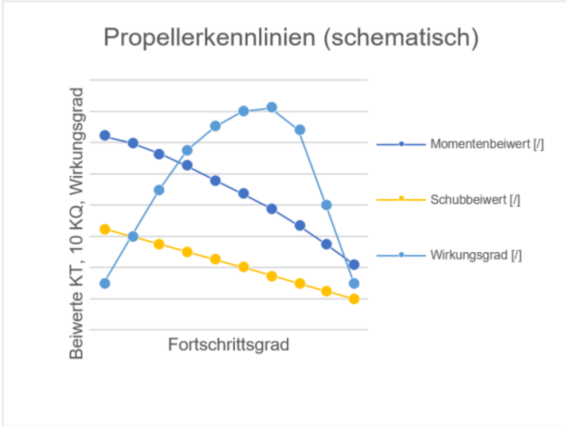


Figure 77 Schematic propeller characteristic curve.

Completely new propulsion principles are possible. So-called surface-piercing propeller blades with much higher moment loads can be realised. Contour or thrust vector controlled propellers support a dynamic load adjustment. The efficiency of the propulsion increases.

Another principle for increasing the hydrodynamic power conversion is the development of inline propulsors. These propulsors are characterized by ring-shaped linear motors on which the propeller blades are arranged in the direction of the axis of rotation. The advantage is the avoidance of blocking by the hub and the formation of the hub vortex. In addition, it is possible to arrange a nozzle in which the linear motor is integrated.

6.3.3 Application examples of propulsion systems

The market with manufacturers and distributors of electric drives and propulsion equipment is continuously developing. In maritime shipping, companies such as Siemens are market leaders for electric POD drives.

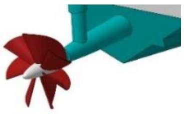
For smaller ferries and passenger ships, the following companies, among others, are successfully active in the market with their system components or complete system installations (motor, propulsion, accumulator, control):

- RAMME Electric Machines GmbH - Inline Thruster linear motors up to 1.6 MW,
- Kräutler Elektromaschinen GmbH - Complete systems up to 100 kW,
- Floren MarineTechnik GmbH - Boat engines and inline thrusters up to 20 kW,
- AQAFORCE GmbH - motor, accumulator system, control system up to 50 kW.

The following table shows the propulsion systems currently in use or under development.

Table: Propulsion for small to medium-sized ferries and passenger ships

Propulsion Suitability for **Accumulator/fuel cell**	**Illustration**	**Typical propulsion characteristics for ferries in inland and coastal shipping**	**Application profile**
Propeller suitable		Power/thrust: 2500 kW / 20 kN Speed: 200 U/min. Diameter: up to 3 m	ferry, passenger ship on inland and coastal waters
Ruder-Propeller conditionally suitable		Power/thrust: 500 kW / 10 kN Speed: 200 U/min. Diameter: up to 2 m	ferry, passenger ship on inland waters

Pod-drive suitable		Power/thrust: 800 kW / 15 kN Speed: 300 U/min. Diameter: up to 1,5 m	ferry, passenger ship on inland and coastal waters
Jet propulsor suitable		Power/thrust: 1000 kW / 20 kN Speed: 350 U/min. Diameter: up to 1m	ferry, passenger ship on inland and coastal waters
Surface-Propeller suitable		Power/thrust: 200 kW / 5 kN Speed: 150 U/min. Diameter: up to 1,5 m	ferry, passenger ship on inland and coastal waters
Supercavitating propeller suitable		Power/thrust: 1000 kW / 25 kN Speed: 600 U/min. Diameter: up to 0,8 m	ferry, passenger ship on inland and coastal waters
Inline-Propulsor geeignet		Power/thrust: 380 kW / 25 kN Speed: 450 U/min. Diameter: 0,6 - 1,5 m	ferry, passenger ship on inland and coastal waters
Jacketed air propeller suitable		Power/thrust: 300 kW / 12 kN Speed: 150 U/min. Diameter: up to 1,8 m	ferry, passenger ship on inland and coastal waters

6.3.4 Drive alternatives for propulsors

Drive alternatives for propulsors are e.g.: hybrid-electric systems. Such propulsion systems are used, for example, as hybrid drives with diesel or gas generator sets on seagoing vessels. Furthermore, hybrid-electric system sets can be realised with fuel cell systems.

Solar energy systems, which support the accumulator energy supply system, can be used as range extension. Among other things, this can be used to compensate for temporary partial or overload conditions of the drive units.

6.4 Use of fibre composites and lightweight construction materials

Modern processes and high-performance materials make it possible to manufacture light boat hulls using additive and automated processes. Hull structures are manufactured in the classic mould construction method using vacuum infusion or RTM-light processes or by special winding/rod winding processes.

Light metal structures are usually welded or riveted constructions. The classic steel shipbuilding processes are still used for connections, force transmission and joining methods.

Despite the decades of use of such materials, there is still considerable potential for development work. In particular the tolerance requirements of the form supported production of FEVW components in connection with welded constructions represent a technical challenge.

Lightweight construction and fibre composite compatible constructions are seldom optimally realised. They require a high degree of target-oriented cooperation between all shipbuilding trades. In many cases, individual manufacturers of components do not have the necessary resources in terms of engineering and production technology.

6.4.1 Fibre composite materials in shipbuilding applications

Fibre composites with different fibre components and fabric structures, single fibres (roving), fabrics similar to textiles or so-called tangled fibre mats (CSM cut glass fibre pieces 38 - 75 mm) form the basis of such components with so-called matrix materials. The most important strength and shape characteristics are only realised in the manufacturing process. This is an essential difference to metal construction. The structure characteristics are defined by the properties of the semi-finished products used.

The structures of the fibre composite components are designed according to the planned load and simulated with numerical methods. For small ferries and passenger ships, the previous processes and applications from boat and yacht building can be adopted.

6.4.2 Use of light metals for shipbuilding structures

In shipbuilding, ferries and passenger shipbuilding, lightweight materials are often used as material substitutes for weight reduction. The light metals aluminium, titanium, magnesium or alloys of these are preferably used. Lightweight constructions, technical metallic connecting elements and fasteners differ significantly from standard steel construction in shipbuilding. Connecting and joining work in lightweight construction usually requires special process environments and conditions. The potential of these materials can only be exploited by using appropriate design methods.

6.4.3 Special manufacturing features

The production-technical specialities essentially consist in the combination of the manufacturing accuracies of metal construction and component structures made of Fibre Compound Materials. Experiences from boat and yacht building show that load-bearing metal components must guarantee a connection in the fibre composite component that is suitable for the design of the FVW. Mould making for hull structures and deck/superstructure is always associated with high expenditure. Flexible, repetitive designs of components are highly cost reducing.

The light metal processing requires different manufacturing process technologies than in the previous steel construction of ships. These manufacturing possibilities must be available at the shipyards as well as at the suppliers.

A special corrosion protection due to electrochemical processes when using light metals in combination with glass fibre or carbon fibre laminates must be considered. There are many possibilities of material combinations with which this problem can be solved.

6.5 Classification and construction regulations for electrically propelled ships

The standards and certification and construction regulations for electrically propelled ships have been harmonised in recent years. This means that the European and international regulations are coordinated and adapted to each other. Nevertheless, the diversity of the individual authorities, responsibilities, associations and insurance structures must be taken into account. It is generally recommended to integrate these activities into the development work already at the beginning of a project.

6.5.1 Inland navigation vessels

For ferries and inland passenger ships, the following rules, among others, apply:

- European Agreement concerning the Carriage of Dangerous Goods by Inland Waterways (ADN),
- Ship Safety Act (SchSG), Ship Safety Ordinance (SchSV),
- Inland navigation regulations, police regulations, regulations of BG Verkehr and DGUV,
- DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 December 2006 laying down technical requirements for inland waterway vessels
- The EU Regulation No. 2016/1628 (NRMM (Non-Road Mobile Machinery) - Regulation) regulates the engines of inland vessels in the categories "IWP" and "IWA" (auxiliary power units).

6.5.2 Vessels in “Bodden” waters, sea waterways and coastal navigation

At present, the rules and regulations of the respective classification and certification companies apply:

- Det Norske Veritas (DNV), Norway and Germanischer Lloyd (GL), Germany,
- Lloyd's Register of Shipping (LRS), United Kingdom,
- Bureau Veritas (BV), France,
- Registro Italiano Navale (RINA), Italy,
- Polski Rejestr Statków (PRS), Poland,
- Maritime Register of Shipping (RS), Russia,
- China Classification Society (CCS), China.

Ships that are used simultaneously on inland waterways, bodden waters, sea waterways and in coastal shipping, such as in classic bathing traffic on the Baltic coast, must comply with both groups of rules.

7 Maintenance, operation and safety of electric ferries

Ensuring reliable operation, high efficiency and profitability, especially in an environment of high and further increasing costs and other influences, are suitable measures to avoid unplanned breakdowns and downtimes. Complex technical systems such as electric ferries, like other technical systems, are subject to wear and tear.

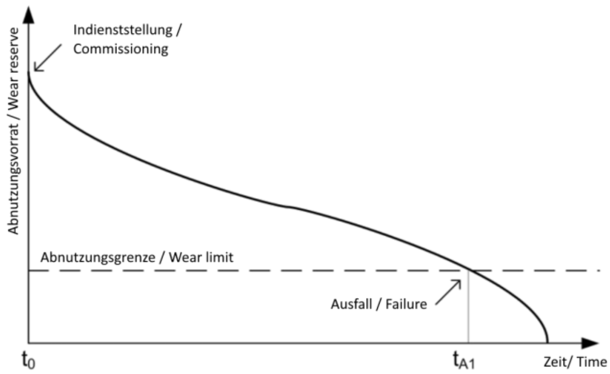


Figure 78 Example of wear and tear until failure. [118]

Example: A defective oil pump for the main engine that fails can cause damage of 50,000 EUR if the damage is not detected early. If the pump is replaced in time, the damage can be reduced considerably. In this case, the price of a new oil pump, e.g. 1,500 EUR, and the damage of 50,000 EUR are offset against each other. Normally, protective mechanisms prevent a total loss of the machine and the costs for the elimination of the failure and the replacement of the pump, are kept within limits. But such a failure can happen at an inopportune moment, when resources such as spare parts or qualified personnel are lacking. And this can lead to consequential problems.

The example only shows the technical side. In complex systems there are often consequential damages that can go beyond the technical system, for example:

- Further material damage,
- Image damage, loss of reputation,
- Damages due to non-fulfilment of contracts (loss, due to one or more journeys not taking place),
- Making amends.

Technical failures, but sometimes also human error, can lead to high, unexpected costs and loss of revenue. It also pollutes the environment and may damage the reputation of the shipping company. The importance of strategic maintenance becomes clear here. With the resources available today, preventive maintenance in particular can be implemented cost-effectively. These investments pay off in the overall operation.

For electric ferries, failures in the charging infrastructure, both onshore and on board, must be taken into account. Usually, charging stations operate during the night in order to charge the battery for the next day. In the event of a breakdown, it may be that no trips can be made the following day.

7.1 Maintenance strategies

Basically, different strategic approaches to maintenance and servicing are known. A summary of these different approaches can be given from experience and literature as follows.

Table: Strategies for repair and maintenance according to [119], [120], [118]

Maintenance strategies				
	Corrective			Preventive
	Failure elimination	Time-dependent	State-dependent	
Objective	Elimination of failures			Avoidance of failures
Property	Response to malfunction, remedy the malfunction	Wear is estimated, service life	Wear is determined	Wear is predicted
Requirements	Speed, technical competence, spare parts available	Planning of resources in time intervals	Inspection by sensor technology	Monitoring with sensor technology, logging, evaluation and modelling
Complexity, system size	Low failure probability, redundancy, low complexity	service life or downtime calculable	Systems that are well monitored, regular inspections	Systems that are well-monitored with sensors and provide valid data for modelling.
Advantages	No costs, as long as no malfunction occurs	Plannability of maintenance, operation, availability	High availability	High availability, cost efficiency of maintenance
Disadvantages	-	No guaranteed availability of spare parts, spare part stocks are not used up (costs)	Costs for the inspection system	Costs for monitoring, analysis system (model)
Risks	-	Random failures between maintenance intervals with increasing failure rate	-	Complexity of troubleshooting, cause analysis, failure analysis increases

The preventive maintenance strategies are divided again into predictive and predictive strategies depending on the source. [118]

As part of the overall operation of electric ferries, the chosen maintenance strategy has to weigh up the costs and benefits and estimate the possible risks and consequential costs in order to achieve an optimal ratio. Thus, basically all classes of maintenance strategies can be applied:

- Shipyard overhaul as part of planned time-based maintenance with routine replacement of parts, maintenance of hull, and wear parts, etc,
- Preventive sensory acquisition of operating and condition data, remote data transmission and evaluation for the purpose of preventive maintenance,
- Reaction to unexpected failures and damage as well as condition-dependent measures.

7.2 Operation of electric ferries

The normal case in the operating practice of a shipping company or fleet operator is a fleet with different ships, different types of ships with different types of propulsion, from different manufacturers, operating at different locations. Without a complete overview of the status of the individual ships, the overview can be lost quickly, and operational planning is impossible. Especially from the point of view of maintenance and repair, technical problems cannot be detected in time.

A comprehensive overview of the technical parameters of the ships at a central and/or decentralized location, as well as the notification of events to responsible technicians who can intervene quickly, is a useful aid for daily operations. Such a system can help to operate a shipping company more economically and sustainably.

Figure 79 Decentralized fleet. [121]

Figure 80 Networking and reporting of vessel status data. [121]

Situation: decentralized fleet with different

- ships of different types,
- Systems on board,
- propulsion systems,
- energy supply systems,
- manufacturers and maintenance companies,
- locations and relations of the ships,
- maintenance and different costs.

Forward-looking cost and resource planning is required for economical and sustainable operation. Work is currently underway to find solutions for the collection and centralisation of maintenance data for ferry shipping, for inland navigation but also for large units.

An example of a manufacturer-independent system is the sensor and data solution from NautiTronix, which makes it possible to ensure technical monitoring and remote diagnosis of the systems on board.

Using NautiTronix' system solution as an example, the functions and modes of operation for preventive maintenance, on-board data acquisition, data evaluation and visualization will be demonstrated and applications for technical maintenance and repair, management decisions and passenger information will be shown.

7.3 Sensor and measuring system and remote data transmission by example

One example is the NautiTronix system, which uses a variety of sensors and measuring systems and transmits the collected data to a central platform. The on-board system units on the ships collect and process the recorded data and send them via wireless internet connection to the central system unit in the shipping company's network. The data can be made available on board units as well as on mobile devices in the form of easy-to-use visualizations, e.g. traffic light system, bar and area diagrams, various map and list views. This provides decision-makers with a quick and reliable overview of the current status of the technical systems and any faults on the ships in the fleet.

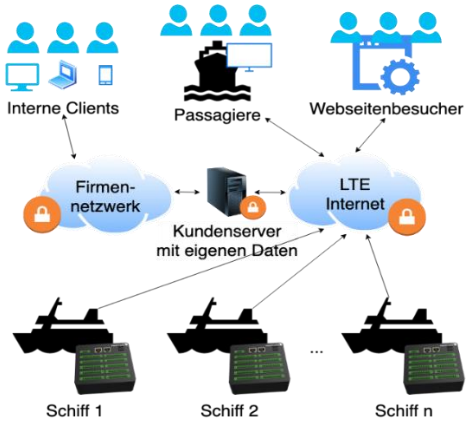


Figure 81 System components and interactions. [121]

7.3.1 Onboard system unit with sensors

The on-board system unit provides the necessary interfaces to the sensors and measuring systems installed in the ship and thus realizes data acquisition and pre-processing of the data. In the case of NautiTronix, this is solved by a special industrial PC which can be retrofitted to all types of ships. Its dimensions (110 x 120 x 45 mm) and design are tailored to the special requirements of maritime and ship operations and can be operated safely over a wide temperature range.

Figure 82 NautiTronix pro Hardware. [121]

Figure 83 Example of hardware installed on a ship. [121]

Special sensors are connected to the on-board system unit via the interface unit. One challenge is the selection of suitable sensors that are able to simulate the sensorium of a good ship mechanic, e.g. to "feel and hear" vibrations, shocks and noises in order to detect damage in time. This is only possible to a limited extent with the sensors and measuring equipment available on the market, which is why our own developments are used for this purpose.

The architecture of the on-board system unit is flexible and open for software and hardware components, so that system extensions to third-party systems as well as further developments of interfaces and new generations of sensors are possible.

For the electric ferries currently in operation, sensors for chargers, solar controllers, battery systems, navigation systems, steering gear, bow thrusters, propellers and propulsion systems are supported by the onboard system unit.

7.3.2 Remote data transmission

With "Cloud" or also "Cloud Computing" we refer here to online-based storage and server services, which are provided on resources of the provider. Therefore, they do not have to be available "on-premises" locally in the ship, in the company or in the head office. Typically, these cloud services are offered by larger external providers who have powerful and secure computing infrastructures and who themselves handle significant data traffic. Examples of such providers are Amazon, Deutsche Telekom or Strato. The advantage is that the characteristics of the provider can be mapped to their own data services, such as IT data security and availability, scalability, current software status and updates.

Operating data is sensitive data. It is in the interest of the operator of a fleet of ships and electric ferries to keep the data in-house. Therefore, a high degree of convenience, security and scalability are required for the practical implementation of data transmission, storage and processing of inspection and sensor data for maintenance.

The systems can be set up in the "cloud" and "on-premises" versions and, since specific IT compliance regulations exist, especially in larger companies, there are various options for connecting to the "cloud": e.g. via Amazon Web Services (AWS), Microsoft Azure, Telekom, and any other external data centers. In the variant "On-Premises", a private data center can be realized on site on own servers. The own server as the "heart" of the platform can, if it is installed "on-premises", guarantee the complete data sovereignty of the user. But the concept of "own data" can also be implemented on a cloud server.

The server imports the transmitted data into the central database using ETL procedures (Extract Transform Load). State-of-the-art data warehouse technologies are used for this purpose; later on, these can be used for further analyses and forecasts, such as machine learning. In order to be "future-proof", there is also the possibility of continuing to store the raw data.

7.3.3 Platform and user interfaces

In addition, it is possible and necessary to provide user interfaces for the data system. Thanks to modern tools and technologies, these can be configured in any way and adapted specifically for the respective users.

Concepts of IoT, workflow, SCADA and predictive maintenance are implemented on the central platform. The data is continuously encrypted and transmitted to the central software platform via LTE connections and standard protocols. The data is buffered in the event of LTE connection failures. Failures lasting up to several weeks can thus be survived without any loss of data. When the connection is restored, the data is transferred. However, it is not possible to evaluate data on the server during this time. Alternative communication channels, e.g. via satellite, can help here if no LTE connections are available on a permanent basis.

The "intelligence of active ship inspection" is located in the back end. By configuring threshold values and more complex rules, problems can be detected early from the sensor data and signalled by "alarms". Deviations from standard parameters, but also more complex alarm conditions are automatically detected, and sources of error can be quickly identified from the "combination of alarms". In the future, this part of the platform will be extended and improved by methods of artificial intelligence.

7.3.4 Visualizations

Problematic events are communicated in the form of alarms. For this purpose, there are either separate alarm views or the possibility to display critical alarms directly. There is also the possibility to signal alarms via email (mobile alarms). Here are examples of a diesel and an electric ship.

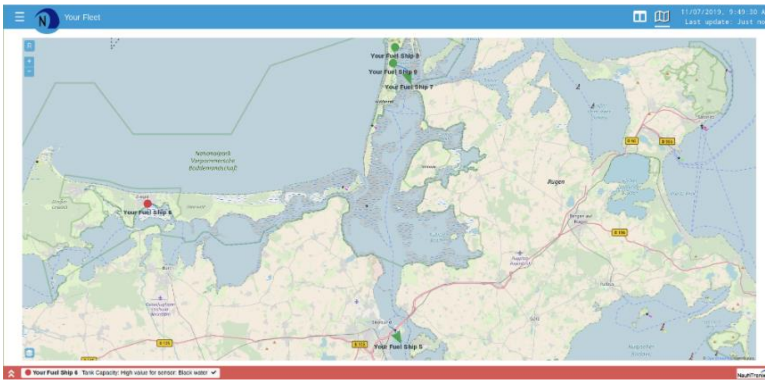


Figure 84 Fleet overview as map display. [121]

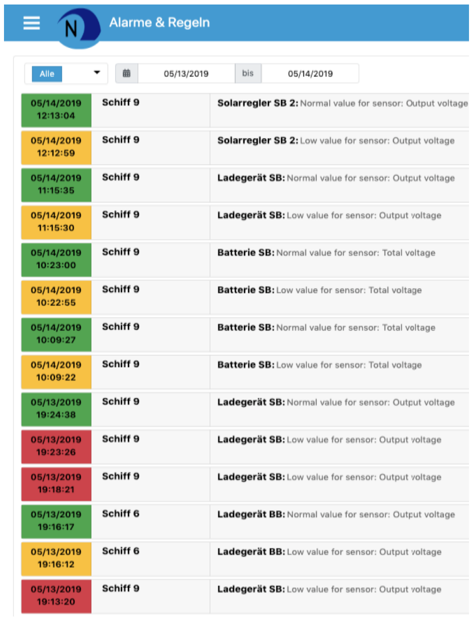


Figure 85 Overview of error messages from ships.

There is also a current overview of the individual components of the ships – in the case of electric ships this is possible up to battery cells:

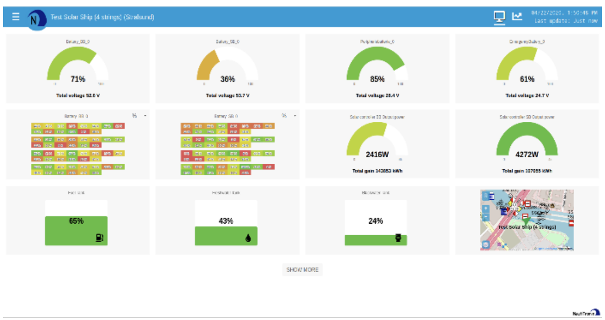


Figure 86 Live data from an electric ship. [121]

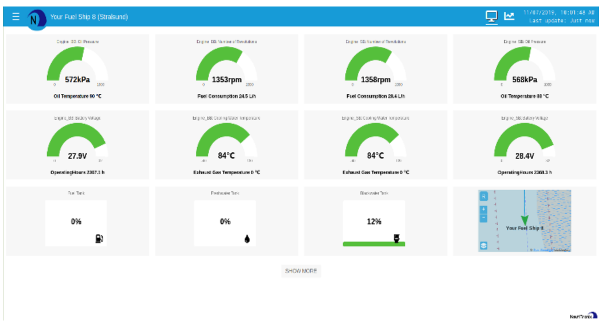


Figure 87 Live data from diesel ship. [121]

Examples for detailed representations.

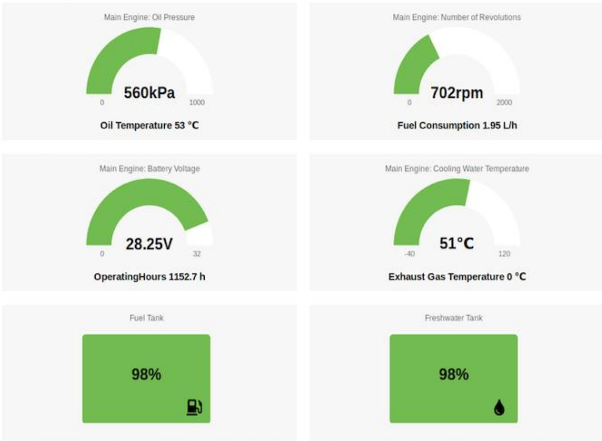


Figure 88 Detail view live data, dashboard. [121]

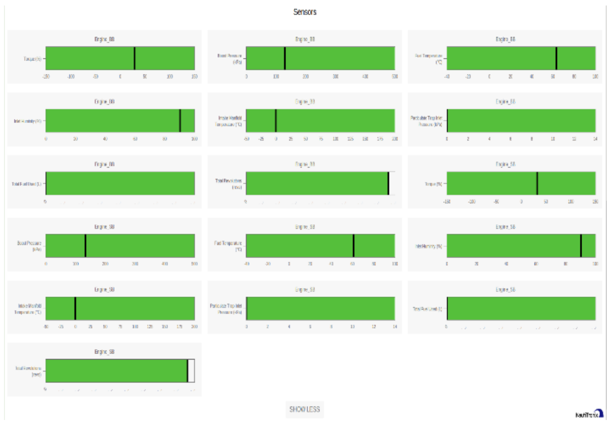


Figure 89 More live data. [121]

Currently NautiTronix supports up to 327 different values per ship. These can be displayed either as dashboards (see above) or as simple lists.

There is also the usual traffic light system: problem sensors are displayed in yellow or red and the sorting is changed according to the degree of relevance.

The following figure shows the visualization as a driving route and as a driving profile with time marks:

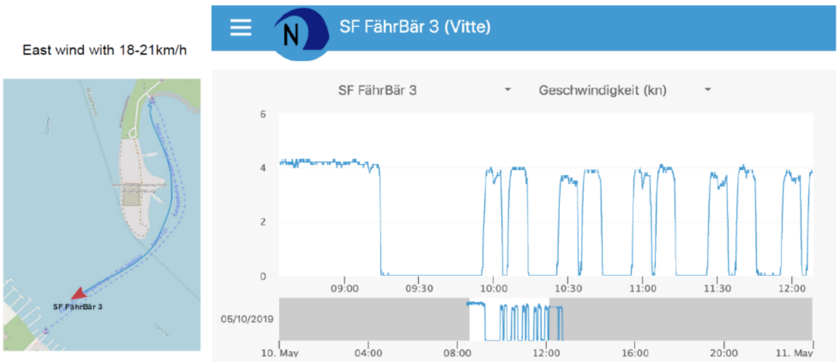


Figure 90 Path of a ship with speed. [122]

7.3.5 Statistical evaluations

In order to evaluate or record events or creeping changes, a lot of data is required. The more data is available, the better the situation can be assessed. Of course, it must be checked from the outset which data are necessary. However, it has often been shown that one should include all data that can be collected from the outset due to the technical conditions, as they are provided by the engine control unit, for example. The temporal resolution plays an important role and depends on the system or component to be measured. Recording a tank content every five seconds does not provide much information. Currents of an electric motor, on the other hand, should be measured every second or faster, depending on the situation, in order to be able to record starting currents and driving profiles. On the basis of the amount of data and its preparation, diagrams can be visualized and decisions can be made in a meaningful way.

Here, too, the temporal classification is relevant. In this way, the crew can be relieved and is able to focus their attention on important events.

By comparing current and historical data, the maintenance department and the ship's command can assess when, for example, the growth on the ship becomes economically too costly, so that cleaning becomes necessary. Indicators that show this abnormality are fuel consumption, engine temperature and speed.

Due to decreasing prices for memory components, it is possible to store data for longer periods of time at reasonable costs. In this way, historical data can be used for various evaluations. At the moment up to four data series can be directly compared:

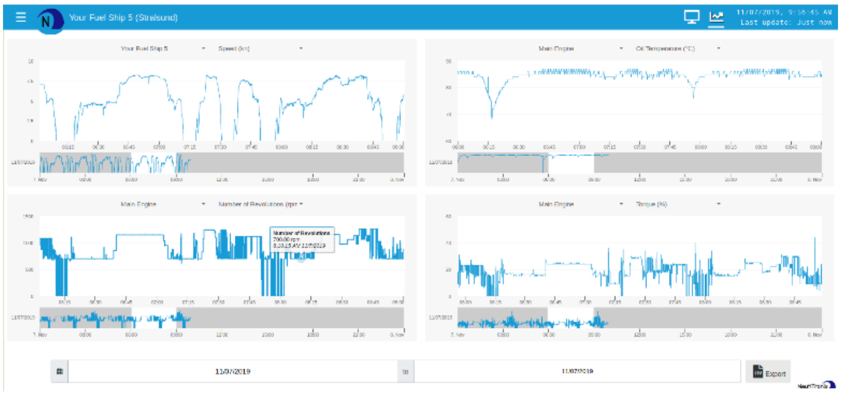


Figure 91 Historische Daten. [121]

Own tools are available for evaluation and visualization. In addition, they can be exported as CSV and processed, evaluated and transferred to third-party systems with any tools.

7.3.6 Added value of operation and maintenance data

In addition to ship inspection, the data collected offer a further added value, namely in the context of problem cases such as accidents. In such cases, questions can be answered by evaluating the data:

- Where was the ship? (positions, route)
- Where were the other ships actually? (locations)
- Did the ships keep to the timetables?
- Did the ship leave the fairway? (proof in insurance matters)

These data are sensitive, and their evaluation is of economic and liability law relevance, e.g. for insurance issues. In this respect, data security is of utmost importance. This applies both to the actual data storage and to all communication channels between the individual components. Here, state-of-the-art encryption and authentication methods are used.

7.4 Savings potentials for operation and maintenance

The ferry business as well as the operation of shipping lines are in strong competition. This situation becomes even more acute when a concession expires. Accordingly, it is essential to always be one step ahead of the competition. Consistently high quality of ferry services, especially in local public transport, has top priority. Shipping companies are under great pressure. Contractual penalties are imminent and mistakes cannot be afforded.

Comprehensive knowledge of the condition of the ship is one way to reduce errors and gain a higher level of safety. Furthermore, costs can be optimized, since wear parts can be used longer until replacement, i.e. they can be replaced depending on their condition or preventively instead of time-dependent.

Remote maintenance as the basis for preventive and sensor-based maintenance provides a significant advantage for shipowners and ship operators compared to the conventional maintenance plan. This advantage can be converted directly into an economic benefit through savings in: Personnel costs for maintenance, repair costs, downtimes and concession penalties, replacement procurement, etc.

The larger the database, the greater its value. Evaluations from the real operation of ships provide valuable design bases for the layout of ships, especially for the use of alternative and new propulsion systems.

7.5 Data as an asset

Ships only generate economic returns when they are sailing and damage that leads to major technical problems is detected in good time. In commercial and ferry shipping, breakdowns always cause considerable losses. Technical failures and human error also burden the environment. Therefore, maintenance and damage prevention measures, especially condition-based and preventive maintenance, are of great importance.

Collected data and their statistical evaluation of the states and behaviour of technical systems under operating conditions are of great benefit for planning and optimisation as well as for the implementation of condition-based and preventive maintenance measures (see the above-mentioned example of fouling of the ship's hull). Because of their usefulness, such data represent an asset with a corresponding market value.

7.6 Additional benefits as a passenger information system

Selected data collected for internal operation can create further additional benefits, for example in the form of a passenger information system.

Selected data is made available to the passengers "publicly" on the ship. In the case of an electric ship with solar energy supply, for example, selected values of this alternative drive technology are also displayed. In addition, the location and the route can be displayed on the map as the passengers know it from other means of transport.

Figure 92 Passenger information with position, speed and power for an electric ship. [121]

The type and quality of information transfer is the responsibility of the shipping company. The following example shows a common diesel ship, where only the position and speed is shown:

Figure 93 Example of passenger information for a diesel ship. [121]

In addition, it is possible to embed selected data and map displays via interfaces (standard REST interfaces with authentication) on your own website and thus make them public.

7.7 Conclusion

Ship's technology doesn't have to fail before it can be repaired. With sensible data acquisition and digital ship inspection, consisting of modern hardware and software, technical faults are pointed out before they occur. In this way, action can be taken instead of reacting. The discussed example of a ship monitoring system realizes a way to implement preventive maintenance. By means of continuous access to selected operationally relevant parameters such as battery level, temperatures or ship position, the status data of diesel and electric ships are permanently collected and autonomously adjusted within defined threshold values by means of an early warning system. This makes it possible to carry out condition-based or preventive maintenance of ships and to conserve resources.

8 Examples of Electric ferries – Charging and refuelling

In the following, ships with electric propulsion and different electric power supply systems will be considered here according to the following classification:

- Battery usage,
- Fuel cell use,
- Hybrid electricity supply based on fossil fuels and batteries,
- Hybrid electric power supply based on synthetic fuels and batteries,
- Nuclear electric power supply.

Since electric propulsion systems are not yet so widely used in shipping, all types of ships are considered with a special focus on ferries. Range-extender variants and photovoltaic systems are shown in the case of battery operation.

8.1 8.1 Battery electric ships

The use of batteries in shipping and there again especially in ferry shipping is already relatively widespread. The reasons for this are the simple handling of a battery system and the increasing use in the automotive sector.

In the following some examples of battery use in boats and ships are listed. Hybrid energy supply systems are dealt with in separate sections.

8.1.1 "Fährbären" („Fährbär 1“ .. „Fährbär 4“)

The company Ostseestaal GmbH & Co.KG has delivered four electric ferries of the type "FährBär" for ferry traffic on the waters in Berlin. The first ships were delivered in 2013.

Figure 94 Views of the "FährBär" type electric ferry. [123]

("FährBär" means "Ferry Bear" because of the heraldic animal of Berlin, where the ferries travel.)

The electric ferry shows the following data [123]:

Design	Catamaran design made of aluminium (handicapped accessible)
Length	18,50 m
Width	5,20 m
Draught approx.	0.60 m
Overall height	3,25 m

Service speed	approx. 8 km/h
Maximum speed	approx. 14 km/h
Power supply	2 x lead gel battery banks with battery management system, Total voltage 48 V, Total capacity: 2 x 720 Ah; 52 solar modules with 205 W each with a total output of approx. 10.6 kWp
Electric drive	2 x Sail-Drive electric motors with 10 kW each, 1 x bow thruster 6 kW
Seating capacity	inside max. 31/35 seats, admission for 49 persons

The ferries are equipped with conventional lead gel batteries. The stored energy is approx. 80 kWh_{el}. The solar modules partially charge the batteries.

The available energy is sufficient to ensure a shuttle service of a few minutes. The batteries are fully charged overnight.

8.1.2 "Sankta Maria II"

In 2017 the company Ostseestaal GmbH & Co.KG delivered the car-electric ferry "Sankta Maria II" for crossing the Mosel between Wasserbillig and Oberbillig (about 170 m). At that time, it was the first fully electric inland ferry in the world.

Figure 95 Car-electric ferry "Sankta Maria II". [124]

The car-electric ferry shows the following data [123]:

Length	28,00 m
Width	9,00 m
Draught	0.80 m
Service speed, (max.)	6 km/h, (13 km/h)
Power supply	2x lithium-polymer battery banks with battery management system, Total voltage: 48 V / 400 V, Total capacity: 24 x 10.5 kWh = 252 kWhel; -15 solar modules with 345 W each with a total output of approx. 5.2 kWp
Electric drive	4 electric motors with 20 kW each
Car / Passengers	6 / 45
Application area	Zone 4 / 3 (without Rhine)

The battery capacity is designed for 13 hours of ferry operation + another 13 hours for safety.

The 15 solar modules installed on board generate electricity for exclusively lighting, radio, air conditioning etc. Lithium-polymer batteries are used here, which correspond to the latest state of the art. The durability of the batteries is indicated with approx. 5.000 charging cycles, which corresponds to a durability of approx. 12 years.

The batteries are charged overnight with shore power in about 6 hours.

8.1.3 "Ampere"

The "Ampere" is a car-electric ferry that was developed as the "ZeroCat 120" project by Fjell-strand shipyard and Siemens for the Norled shipping company. Since 2015, it has been sailing the approximately six-kilometer crossing of the Sognefjord on route E39 between Lavik and Oppedal north of Bergen in Norway. The crossing takes place every 20 minutes, 34 times a day, purely electrically [125], [126].

Figure 96 Car-electric ferry "Ampere". [127]

Technical data of the „Ampere“ [128], [129]:

Length	80 meters
Width	21 meters
Transport capacity	120 cars / 360 passengers
Crossings	34 per day
Distance	6 km
Travel time	20 minutes, (30 km/h)
Operating time	365 days per year
Charging time	10 minutes
Energy per crossing	200 - 250 kWh
Power supply system	1040 kWh; 160 x Corvus energy AT6500 modules, lithium-ion battery (20 tons) Corvus.
Electric drive	800 kW
Charging station on land	Each shore with 410 kWh; 63 x Corvus AT6500-LQ (Liquid-Cooled) modules

The electric ferry was designed for emission-free operation, by using the catamaran shape and aluminium as shipbuilding material. Compared to traditional ship forms, the ferry has a lower travel resistance and has only half the weight of the other ferries on the line.

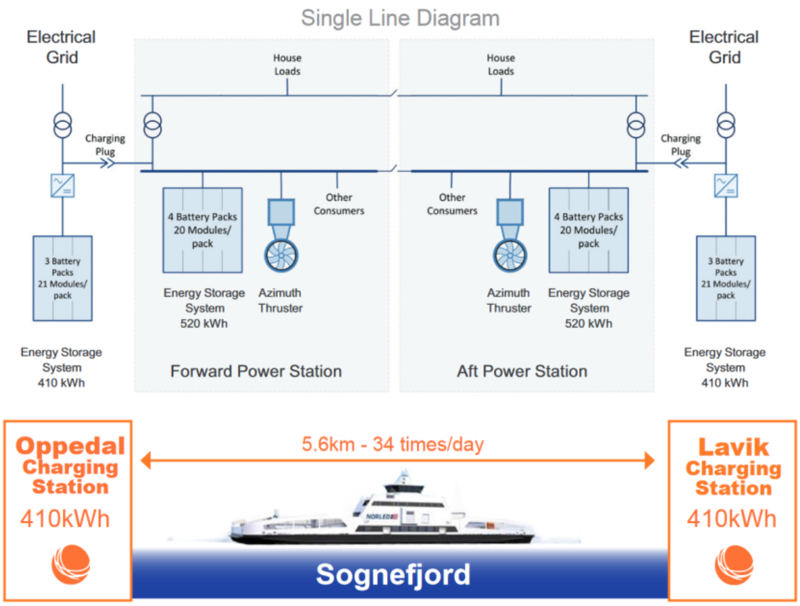


Figure 97 Diagram of the electric drive system and power supply system. [129]

The special feature of this electric ferry is the relatively large drive power of 800 kW and battery energy of 1 MWh as well as the special charging process.

8.1.4 "Ellen"

The Ellen is an electrically operated ferry in Denmark. The ferry of the shipping company Ærøfærgerne started its ferry service between the southern Danish ports of Fynshav (east coast of the island of Als) and Søby (island of Ærø) in August 2019.

The ferry is equipped with 4.3-MWh accumulators. The accumulators are automatically charged during the berthing period in Søby. The consumption of the ferry is approximately 1,650 kWh per round trip. In the medium term, the ship's electricity requirements are to be covered completely by renewable energy sources, so that the ferry can be operated in a CO2-neutral way [130].

Figure 98 Car electric ferry „Ellen". [131]

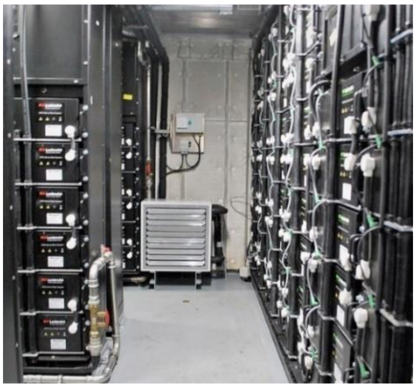


Figure 99 Battery room car-electric ferry „Ellen". [132]

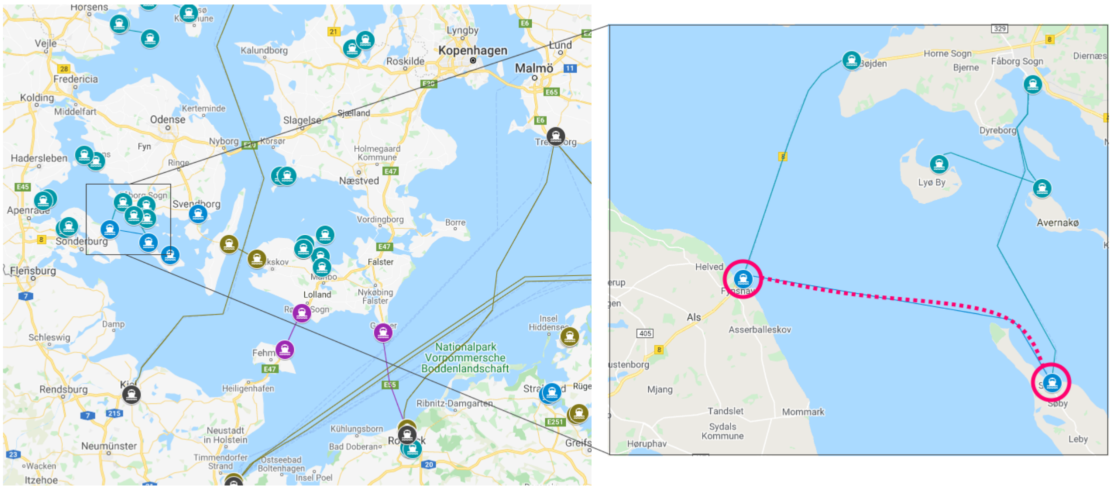


Figure 100 The route of the "Ellen". [133]

Technical data of the „Ellen“ [134], [135], [130]:

Length	59,50 m
Width	12,80 m
Transport capacity	31 cars / 147 passengers
Travel time	60 minutes
Speed	25 km/h (14 kn)
Power of electric motor	2 with 750 kW each
Energy supply system	4.3 MWh (Leclanché)
Energy consumption	1,650 kWh for one round trip Søby - Fynshav and back, shop in Søby
Distance	40 km, for a round trip Søby - Fynshav and back

8.1.5 Scandlines „Vogelfluglinie“

There is a similar project from the Scandlines shipping company, which has been under discussion for some time, concerning the electrification of the "Vogelfluglinie", the 19 km long crossing of the Fehmarn Belt between Puttgarden and Rødbyhavn. Due to the tight timetable, the challenge in contrast to the "Ellen" is that only 10-12 minutes are available to recharge the energy for a crossing of 4 MWh. Details are given in the appendix.

8.2 Fuel cell ships

Fuel cell use in shipping is still very marginal. This is due to the fact that a fuel cell system is much more complex and cost-intensive than a battery system and that direct hydrogen supply is not sufficiently accepted. Indirect hydrogen supply, e.g. via methanol, which is widely accepted in terms of handling and safety, is still in the development stage.

Below are some examples of fuel cell use in boats and ships.

8.2.1 Zemships project

The project Zemships (Zero Emissions Ships) aims at the development of a hydrogen powered passenger ship on the Alster in Hamburg.

The ship named FCS "Alsterwasser" has the following data [136]:

Length	25.56 m
Width	5,2 m
Height	2.65 above waterline (body can be lowered hydraulically by 0.35 m)
Draught	1.2 m (unattended) - 1.33 m (with passengers)
Energy supply	12 tanks each 178 litres (50 kg H2), 350 bar; 2 × 48 kW PEFC fuel cells (140 V DC); Proton Motor Fuel Cell GmbH; 7 lead gel batteries (80 V each in series) 360 Ah
Electric drive	Three-phase electric motor (100 kW); bow thruster (20 kW)
Speed	14 km/h (7.6 kn)
Transport capacity	100 passengers

The principle function can be derived from the following simplified representation of the structure of the energy supply and the drive.

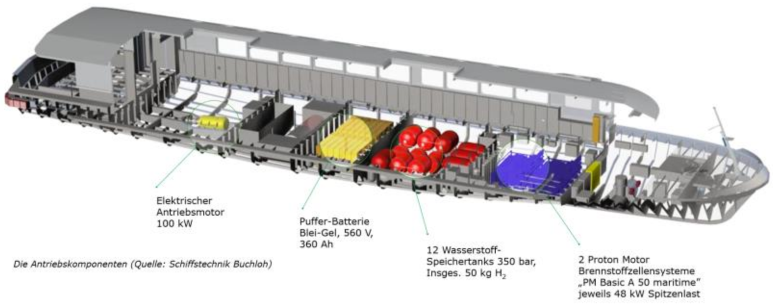


Figure 101 Simplified representation of the structure of the energy supply and electric drive of the FCS „Alsterwasser". [136]

The major part of the energy supply is supplied by hydrogen in the 12 tanks, 178 l each at 350 bar, and the fuel cell system. The hydrogen energy is 2,000 kWh_{H2}. If an average efficiency of the fuel cell system of approx. 40 % is assumed, an electrical energy of 8,000 kWh_{el} is available. This electrical energy will then enable the FCS "Alsterwasser" to operate for about 8 hours.

The batteries have an electrical energy of 200 kWh_{el}. They are used to start up the fuel cell and to provide additional power when the power requirement is greater than 96 kW_{el} (max. electrical energy of the fuel cell system). These high power requirements are often to be expected during manoeuvring, for approaching as well as starting and stopping.

Figure 102 FCS „Alsterwasser" at its H2 filling station. [137]

8.2.2 Passenger ship "Innogy

The "Innogy" is a passenger ship with electric propulsion and an electric power supply based on high-temperature polymer electrolyte fuel cells (HT-PEMFC), which operate in the temperature range of 120 to 180 °C (figure). The hydrogen for supplying the fuel cells is produced from methanol by means of a reformer.

Figure 103 Passenger ship „Innogy" [138], [139]

The "Innogy" (ex. FGS "Inselstadt Ratzeburg") shows the following data [138], [139]:

Length	29,00 m
Width	4,80 m
Draught	0,55 m
Energy supply	Tank capacity methanol: 330 l; 7 HT-PEMFC per 5 kW; Accumulators with 120 kWh_{el}
Reserve	Volvo D7CTA diesel engine 180 kW with 80 kW electric generator
Electric drive	80 kW
Transport capacity	180 passengers
Distance	up to 16 hours on the Baldeneysee in Essen

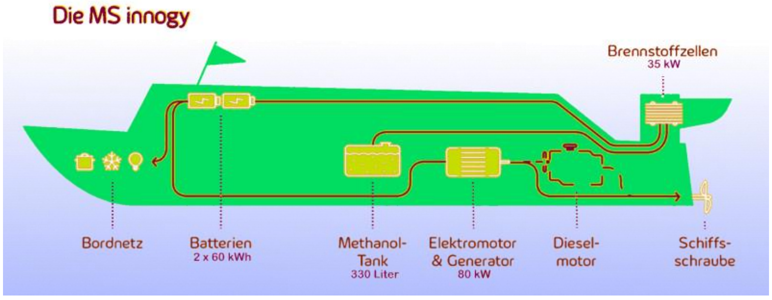


Figure 104 Illustration of the structure of energy supply and drive of the „Innogy“ [138]

Here, the batteries are also used to start the fuel cell and to provide additional power for high performance requirements. A diesel engine with an electric generator serves as a safety reserve. The MV "Innogy" can run electrically for up to 16 hours on Lake Baldeney, near Essen. Afterwards the methanol tank has to be refilled. [138], [139]

8.2.3 Project "ELEKTRA"

The project "ELEKTRA" is a research project dealing with the development of an energy-efficient hybrid powered inland push boat and was funded by the Federal Ministry of Transport and Digital Infrastructure. [140]

With the "ELEKTRA", a hybrid propulsion concept consisting of fuel cells and accumulators is to be demonstrated on an inland waterway vessel and their dynamic interaction during operation of the vessel is to be researched and optimized with regard to the maximum range of the vessel.

Within the project, concepts for the development of infrastructural measures for charging the accumulators with shore power and for supplying the fuel cells with hydrogen will be developed. Furthermore, an energy management system will be developed, which will optimally use the limited energy on board under consideration of the operating situation. For the first time, a driving assistant with integrated route planning for inland navigation will be developed and optimized to enable an increase in range. The economic efficiency and competitiveness compared to conventionally driven inland navigation vessels and in general inland navigation compared to other modes of transport shall be strengthened.

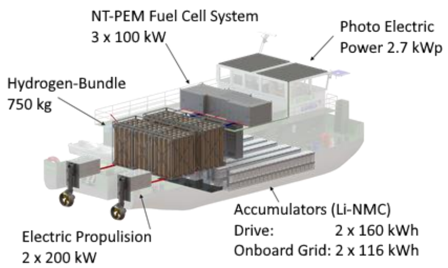


Figure 105 Presentations of the project „ELEKTRA“ [140]

Figure 106 Illustrations of the „ELEKTRA“ project.

8.2.4 "HySeas III" project

Another example of an electric ferry to be equipped with a fuel cell is the HySeas III project. [141], [142]

HySeas III was launched in July 2018 for the construction of a deep-sea ferry. It is being built at the Scottish shipyard Ferguson Shipbuilders in Glasgow and is scheduled to sail between the Orkney Islands in 2021. The ferry will run on fuel cells and hydrogen as fuel. The required hydrogen will be produced at Orkney Island Eday by the European Marine Energy Center (EMEC) with a 0.5 MW polymer electrolyte membrane electrolyzer. The electricity comes exclusively from wind, wave and tidal power plants. The fuel cell for the ferry is supplied by Ballard Power Systems.

The project is to be the world's first hydrogen-powered ocean-going ferry with fuel cells. It is supported by the EU (Horizon2020 program). Project coordinator and main partner is the Scottish University of St. Andrews. Partners are Ferguson Marine Shipyard, the German Aerospace Center (DLR), Orkney Island Council, Ballard Power Systems (Denmark), Kongsberg Maritime (Norway), Interferry (Belgium) and McPhy (France).

Figure 107 Deep-sea ferry "HySeas III". [143]

Figure 108 Deep-sea ferry "HySeas III". [142]

Table: [144]

Dimensions	40m (length) × 10m (beam) × 4m (depth)
Passengers	120
Rolling cargo	20 passenger vehicles or 2 trucks
Power supply	On-board fuel cell; Proton-exchange membrane fuel cells (PEMFC)
Power	600 kW
Hydrogen storage	600 kg, pressure storage 350 bar
Battery storage	768 kWh; Li-ion,
Distance	7 km; Kirkwall - Balfour; 20 minutes, (ca. 14 km/h)
Estimated energy	250 - 350 kWh; per crossing

The North Scottish islands have a massive surplus of renewable energy from wind and tidal power, which is to be solved by developing a hydrogen economy in the Orkney Islands region and combining it with the HySeasIII ferry project. In some regions of the Baltic Sea the situation is comparable. Therefore, the HySeasIII can be a good model for similar projects.

8.3 Hybrid electricity supply with fossil fuels

The ferries operated by Scandlines Deutschland GmbH are very good examples of a hybrid electric power supply and electric propulsion system based on fossil fuels and batteries.

In Europe, Scandlines Deutschland GmbH began converting the ferry "Prinsesse Benedikte" to hybrid drive on the Puttgarden-Rødby route in 2013. This was followed by the conversion of three other ferries on this route. In 2016, two new ferries with hybrid drive were then put into service on the Rostock-Gedser route. The picture shows one of the new ferries of type "Berlin".

Figure 109 Hybrid ferry „Berlin". [145]

The ferry is equipped with three electric power supply systems based on diesel-electric generators. Two further diesel engines are provided for direct propulsion on controllable pitch propellers. In addition, there is a battery system which is charged by the diesel electric generators. Battery operation is only used when entering ports in order to reduce local emissions.

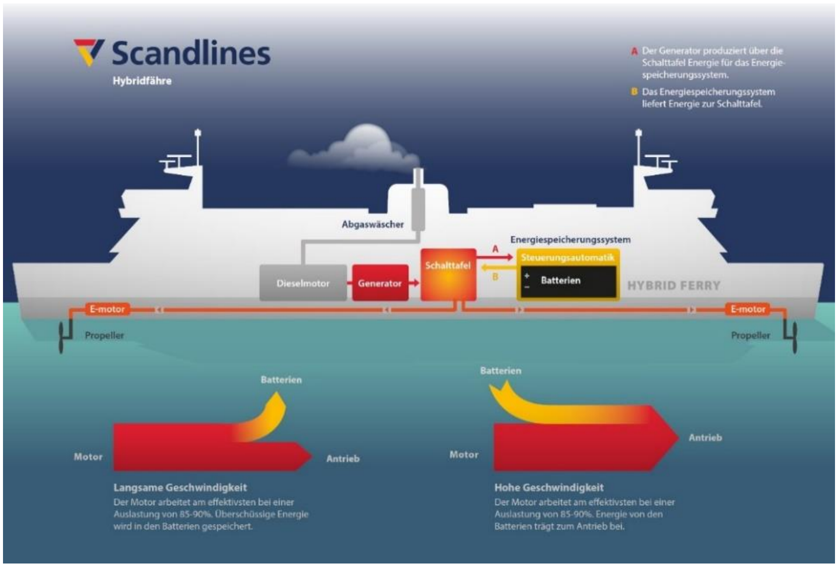


Figure 110 Principle of the power generation and propulsion system of the „Berlin" [146]

In normal operation, only two or three diesel generators are in operation, each with a capacity of 40-55% at sea and 8-10% in port. However, the generators work most efficiently at a load of 85-90%.

By running the battery pack in parallel with the remaining diesel generators, a constant, optimum load of 85-90% of the generators can be achieved. This saves fuel and is less harmful to the environment. Scandlines is the first shipping company in the world to be able to store surplus energy on this scale in batteries on board since 2013. [146]

Technical data of the „Berlin“ [147]:

Length	169.50 m above sea level
Width	25.40 m a.s.l.
Height of keel to weather deck	14.25 m
Max. Draught	6,00 m
Service speed	27,5 km/h (21 kn)
Energy supply	main diesel generator 4,500 kW, Hybrid engine 4,500 kW (electric motor or generator operation), Port diesel generator 1,540 kW, Main diesel generator 4,500 kW, Battery storage 1,500 kWh
Propulsion	Diesel engines 2 x 4.500 kW on controllable pitch propeller, Hybrid engine via clutch on controllable pitch propeller, Azipull-thruster 2 x 3,500 kW, Bow thruster 2 x 1,350 kW; exhaust gas scrubber (SO2 closed-loop scrubber) 4 x 4,500 kW
Transport capacity	96 trucks or 460 cars, 1,300 passengers
Distance	about 49 km

8.4 Hybrid electric power supply with synthetic fuels

Synthetic fuels are to be understood here as e-fuels (synthetic fuels from renewable electrical energy sources) and BtL (fuels from biomass).

The only known examples of ships with electric propulsion and hybrid electric power supply based on synthetic fuels and batteries are projects in which biodiesel is used in diesel engines. For example, the use of biodiesel on the inland waterway vessel "For Ever" from the Netherlands [148] is mentioned. However, this ship does not have an electric propulsion system. In addition, companies have set up tank facilities in the port of Rotterdam to refuel ships with biodiesel [149].

The Hurtigruten companies are planning first test runs with biodiesel [150], 2019). Especially the new cruise liners "Roald Amundsen" and "Fridtjof Nansen", which are equipped with diesel generators, batteries and electric propulsion, would then be the first ships based on a hybrid electric power supply based on synthetic fuels and batteries. The batteries have an energy of 1,360 kWh. This means that a voyage of only 20 to a maximum of 30 minutes is possible. An upgrade by a factor of three to approx. 5,000 kWh is planned [151]

Figure 111 Cruise ship „Roald Amundsen“ [152]

As already mentioned in a previous section, e-fuels must be viewed critically with regard to environmental impact and energy consumption. BtL fuels are not the first choice in terms of competition for land for food production and environmental pollution. Hope for acceptable BtL fuels could arise from a new process using wheat straw [153].

There have also been and will continue to be experiments with the use of methanol in diesel engines [154]. Even though the used methanol there was not produced in a CO2-neutral way. Since methanol can be produced with relatively little effort and low process energy, there are great opportunities for CO_2-free production.

8.5 Nuclear electrical power supply

Nuclear energy supply is primarily found in the military sector of shipping. The high energy density of nuclear energy sources allows very long ranges as well as high power for ship operation and modern weapon systems. The very high costs are relevant in this sector but are borne in the interest of national safety.

In the marine sector, three trends are shaping the future of ship technology:

- the all-electric ship,
- the stealth technology and
- the coastal ships.

The all-electric ship propulsion concept for the future power supply for surface combat ships was adopted from cruise ships. An example for a fully electric ship is the new generation aircraft carrier CVN-78. [155], [156]

An electric propulsion system gives the ship designer possibilities to locate the equipment wherever he wants to optimize the weight and balance of the ship and connect it with electric cables. This increases, among others, the survivability of the ship. [156]

In the civil merchant shipping sector, four ships have so far been built and are in service temporarily and partially. These ships are not equipped with electric propulsion, but with steam turbine propulsion. One of them is the ice-breaking merchant vessel "Sevmorput" [157], which is used especially for the North-East Passage. There are also four nuclear-powered icebreakers in operation and three under construction, which are all equipped with electric propulsion. The following data are known for the icebreaker "50 Let Pobedy": [158]

Figure 112 Icebreaker „50 Let Pobedy“ [159]

Length	147.90 - 159.60 m (loa)
Width	30,00 m
Height	17,20 m
Draught	max. 11,00 m
Tonnage	20,646 - 23,439 BRZ
Engine	3× electric propeller motors, 17.6 MW each; shaft system
Engine power	52,800 kW (71,788 PS)
Maximum speed	38,5 km/h (21,5 kn)
Energy supply	nuclear-electric, 2× nuclear reactor (OK-900A), each 171 $MW_{therm.}$, 2× steam turbine (TGG-27.5 OM5), 27.6 MW each
Generator output	55,200 kW (75,051 PS)
Propeller	3× 4-blade fixed pitch propeller, Ø 5,7 m
Radius of action	almost unlimited

8.6 Charging and refuelling infrastructure

8.6.1 Charging infrastructure for electric ferries with batteries

In many cases, the normal shore connection is currently used to supply boats and ships for charging the batteries, as shown in the figure.

In many cases, these charging stations are supplied by decentralised power generation systems. In some cases, even by means of photovoltaic and/or wind power plants.

For the large electric ferries, such as "Ampere", special electric filling stations (see figure) have been implemented in order to be able to transmit large currents within a short charging time (e.g. 10 minutes) by means of largely automatic plug systems. As an example the charging infrastructure in Lavik (Sognefjord/ Norway, see Figure below) has 1 = vacuum mooring system, 2 = charging crane, 3 = charging current connector in the pantograph version, 4 = battery energy storage for fast charging.

Figure 113 Shore power supply at the Rheinauhafen in Cologne. [160]

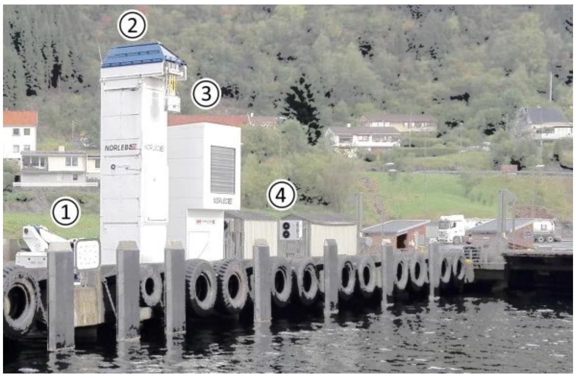


Figure 114 Charging infrastructure of the "Ampere". [161]

Because the electricity grid in both ports is too weak to provide the necessary 1,250 KW charging power for the ship batteries, batteries with a capacity of 390 kWh were installed at the moorings in both ports. During the approximately 50-minute absence of the ship, the batteries are charged with lower power from the shore grid and the stored energy is transferred to the ship's batteries with high charging power during the approximately 10-minute berthing period with a plug system in the form of a pantograph [125].

8.6.2 Infrastructure for refuelling ships with hydrogen

The hydrogen filling station of the passenger ship FCS "Alsterwasser" of the Zemships project is a good example for the refuelling of ships with hydrogen. It is also unique in this way in Europe. The following diagram shows the H2 refuelling infrastructure.

The hydrogen is delivered to the filling station in liquid form and stored there in a 17,000-litre liquid hydrogen tank. The liquid hydrogen is then brought to a gaseous state of 450 bar by a compressor arrangement and stored in a high-pressure buffer.

The ship was refuelled at 350 bar using a GH2 dispenser positioned at the dock.

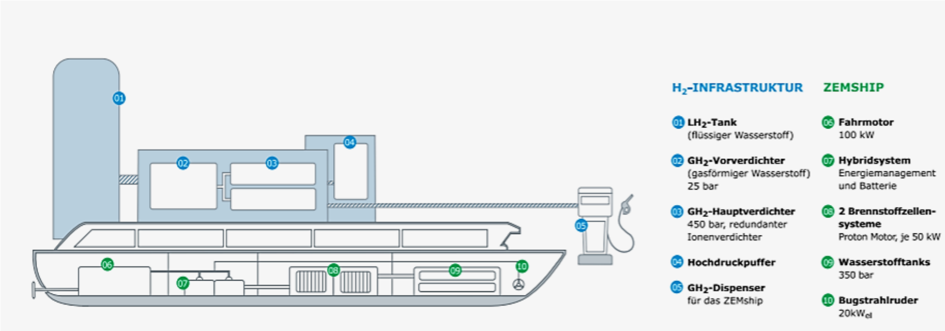


Figure 115 B Refuelling infrastructure with simplified representation of the energy and propulsion structure of the FCS „Alsterwasser" [136]

8.6.3 Infrastructure for methanol refuelling

Methanol is very similar to motor gasoline and ethanol in many of its basic characteristics. Note the relatively low flash point of 11 °C and the special toxic and corrosive effect. In [154] the following statements are made on the legal framework of transport and storage:

Methanol can be transported by road, rail or pipelines, thus enabling easy and cost-effective long-distance transport of renewable energies. Special stowage guidelines set out in the IMDG Code apply to sea transport. Depending on the number of passengers on board, stowage is only permitted on deck. On board, the tanks used for transport must withstand the conditions at sea, which must be taken into account in the design and the inspection and test regulations. Among other things, dynamic loads, vibrations of the ship's operating equipment, ambient temperatures and salty air must be taken into account in the planning of the transport system.

Another potential besides the use of existing transport infrastructures is the storage infrastructure of methanol, which is spread all over the world. In Germany, national storage regulations are regulated by the Industrial Safety Ordinance and the Hazardous Substances Ordinance as well as the downstream regulations TRBS (Technical Rules for Industrial Safety) and TRGS (Technical Rules for Hazardous Substances) of the Federal Institute for Occupational Safety and Health.

Figure 116 H2-liquid hydrogen tank with compressor and buffer tank. [137]

Figure 117 GH2 dispenser at the pier. [136]

Due to the corrosive nature of methanol, further modifications to the fuel system are planned, which have been established on land for decades. Couplings, pumps, filters and valves must be adapted to the use of methanol.

From the above illustrations it can be deduced that a methanol refuelling structure can be realised at any time. No new technological developments are necessary and the effort is comparable to conventional filling stations for ethanol and motor gasoline.

9 Assessment and conclusion

9.1 Evaluation of technical systems for the suitability as electric ferry

9.1.1 Evaluation criteria

Production costs or investment costs and energy costs are not shown, but only the corresponding personnel and material costs. This is considered under PA and MR (see table).

A monetary consideration is neither meaningful nor target-oriented, since the costs of environmental damages would be significantly higher if adequate protection measures were not taken.

The following assessment is only of an estimated nature. It is based on the findings of the previous sections as well as on generally known engineering knowledge and diverse information from the literature. Special features are dealt with separately.

Abbreviations for the following tables:

ED	Energy densities,
LBZ	Loading or refuelling time,
HD	Handling: - Aggregate state liquid under normal conditions, 15 °C, 1 bar. - Liquid, cryogenic, - Gaseous > 300 bar, behaviour at low temperatures,
SI	Security,
SZ	System reliability,
TO	Toxicity,
EE	Energy efficiency of energy conversion,
EP	Energy efficiency in production and material procurement for transport, Raw material extraction and processing,
MR	Material Resources,
PA	Production effort,
UB	Environmental impact in material procurement, production and operation,
KB	Climate impact during material procurement, production and operation.

9.1.2 Evaluation of the types of energy supply independent of the application scenario

		Evaluation criteria											
No.	**Power supply types**	**ED**	**LBZ**	**HD**	**SI**	**SZ**	**TO**	**EE**	**EP**	**MR**	**PA**	**UB**	**KB**
1	Battery system	-	-	++	++	+++	++	+++	-	-	+++	-	++
2	Fuel cell system with direct H2 supply	+	++	+	+	++	++	++	++	++	++	++	++
3	Fuel cell system with indirect H2 supply (e.g. methanol)	++	++	++	++	++	-	+	+	+	+	++	++ 1)
4	Hybrid solution: Thermal power machines with fossil fuels and battery	++	++	++	++	+	-	+	+	+	+	-	-
5	Hybrid solution: Thermal power machines with direct H2 supply and battery (no examples available)	+	++	++	++	+	++	+	+	+	+	+	++
6	Hybrid solution: Thermal power machines with CO2-neutral fuels (synthetic fuels) and battery	++	++	++	++	+	-	-	+	-	+	-	++
7	Nuclear electricity supply	+++	++ 2)	++	++	++ 3)	-	+++	++	++	-	++	++

1) Provided that the CO2 for the chemical in which H2 is bound comes from CO2-free or CO2-neutral sources.
2) Loading with nuclear material is relatively lengthy (a few days), but only at very long intervals (up to several years).
3) Due to the high effort for safety, a high system reliability is also given.

9.1.3 Evaluation of energy supply types depending on the range

No.	Energy supply types	Range in coastal and Inland waters				Range on the high seas	
		< 1 km	**1 bis 10 km**	**10 bis 50 km**	**>50 km**	**bis 50 km**	**>50 km**
1	Battery system	++	++	+	-	-	-
2	Fuel cell system with direct H2 supply	-	-	+	-	+	-
3	Fuel cell system with indirect H2 supply (e.g. methanol)	+	+	++	++	++	++
4	Hybrid solution: thermal engines with fossil fuels and battery	-	-	-	+	+	++
5	Hybrid solution: Thermal engines with direct H2 supply and battery (no examples available)	-	-	-	+	+	-
6	Hybrid solution: thermal engines with CO2-neutral fuels (synthetic fuels) and battery	-	-	-	+	+	+++
7	Nuclear electricity supply	-	-	-	-	-	+++

9.2 Conclusion

Electric ferries or the electrical operation of shipping lines requires an all-encompassing, new and innovative configuration of the vehicles in terms of design, propulsion and electrical power supply, as well as the ferry berths and refuelling infrastructures. As was shown by the selected examples, planned projects and realised ferry lines, the necessary solutions and innovations are available.

The biggest challenge is the electrical power supply and the concrete configuration depends mainly on the range and the area of application of the ferry.

- For ranges of up to approx. 10 km in inland and coastal waters, battery systems for electrical power supply are the most advantageous solution. They offer high efficiency, easy handling and high reliability.
- For ranges of 10 km to approx. 50 km, fuel cell systems with indirect hydrogen supply, e.g. CO2-neutral methanol, are more advantageous than battery systems. Battery systems for these ranges already require a very large volume and weight. In addition, the volumetric energy density of a fuel cell system with methanol as the hydrogen carrier is about a factor of 10 greater than the battery systems currently available.
- For ranges greater than 50 km or use at sea, hybrid solutions for electrical power supply are still to be chosen, as fuel cell systems for power ranges >300 kW are not yet available. CO2-neutral fuels (e.g. biodiesel) are to be preferred for hybrid solutions.

10 Appendix

10.1 SI basic units and definitions

The International System of Units (Système International d'Unités - abbreviated SI in all languages) was introduced in 1960. In many countries the SI units were legal units for official and commercial traffic.

On 16 November 2018, the International Conference on Weights and Measures decided to make a fundamental change to the International System of Units (SI). The basis for measurement is now natural constants (and not basic units, as before). The changes came into force on 20 May 2019. [162], [163]

Table: Basic parameters as defined from May 2019.

Base unit ***Natural constant***	**Explanation**
The Metre	is the length of the distance that light travels in a vacuum for a period of (1/299792458) seconds.
as of May 2019:: *Speed of light*	is the SI unit of length. It is defined by setting the numerical value 299792458 for the speed of light in vacuum c, expressed in the unit m/s, where the second is defined by $\Delta\nu$Cs. From May 2019, the natural constant of the speed of light in a vacuum will form the basis.
The Kilogram	is the unit of mass; it is equal to the mass of the International Prototype Kilogram.
as of May 2019: *Planck- constant*	is defined by establishing for the Planck constant h the numerical value $6{,}62607015 \times 10^{-34}$, expressed in the unit J s, which is equal to kg m^2 s^{-1}, the metre and the second being defined by c and $\Delta\nu$Cs.
The Second	is 9192631770 times the period duration of the radiation corresponding to the transition between the two hyperfine levels of the ground state of atoms of nuclide 133Cs.
as of May 2019: *Frequency caesium 133Cs*	is defined by setting the numerical value 9192631770 for the caesium frequency $\Delta\nu$ Cs, the frequency of the undisturbed hyperfine transition of the ground state of the caesium atom 133, expressed in the unit Hz, which is equal to s^{-1}.
The Ampere	is the strength of a constant electric current which, flowing through two parallel, rectilinear, infinitely long conductors of negligibly small, circular cross-section, arranged in a vacuum at a distance of one metre from each other, would cause the force 2 10^{-7} Newton between these conductors per metre of conductor length.
as of May 2019: *Elementary charge*	is defined by establishing for the elementary charge e the numerical value $1.602176634 \times 10^{-19}$, expressed in the unit C, which is equal to A s, the second being defined by $\Delta\nu$ Cs.
The Kelvin	is the unit of thermodynamic temperature, is the 273.16th part of the thermodynamic temperature of the triple point of water.
as of May 2019: *Boltzmann constant*	is the SI unit of thermodynamic temperature. It is defined by establishing for the Boltzmann constant k the numerical value $1{,}380\,649 \times 10^{-23}$, expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}, where the kilogram, the metre and the second are defined by h, c and $\Delta\nu$ Cs
The Mol	is the amount of matter in a system consisting of as many individual particles as there are atoms in 0.012 kilograms of the carbon nuclide 12C. When using the mole, the individual particles must be specified and can be atoms, molecules, ions, electrons, and other particles or groups of such particles of specified composition.
as of May 2019:: *Avogadro constant*	contains exactly $6.02214076 \times 10^{23}$ individual particles. This number corresponds to the fixed numerical value for the Avogadro constant NA, expressed in the unit mol^{-1}, and is called the Avogadro number The amount of substance, character n, of a system is a measure for a number of specified individual particles. A single particle can be an atom, a molecule, an ion, an electron, another particle or a group of such particles with a specified composition.

Base unit *Natural constant*	**Explanation**
The Candela	is the luminous intensity in a given direction of a radiation source emitting monochromatic radiation of frequency 540 x 1012 Hertz and whose radiant intensity in that direction is (1/683) watts through steradian.
as of May 2019: numerical value	is defined by establishing the numerical value 683 for the photometric radiation equivalent Kcd of monochromatic radiation of frequency 540 x 10^{12} Hz, expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1} or cd sr kg^{-1} m^{-2} s^3, the kilogram, the metre and the second being defined by h, c and $\Delta \nu$ Cs.

Table: Previous base units and base values

Basic variable	**Base unit**	
	Name	**Symbol**
Length	Meter	M
Mass	Kilogram	kg
Time	Second	S
Electric current	Ampere	A
Temperature	Kelvin	K
Quantity of substance	Mol	mol
Luminous intensity	Candela	Cd

10.1.1 SI attachments

Attachments are needed to express the multiple of a size. The following names have been established for the powers of ten.

Examples

- One says: "one mega watt" and writes 1 MW for 1000,000 W (power).
- One says: "one nano meter" and writes 1 nm for 0,000.000.001 m. (length)

Note the special feature: The SI unit "The kilogram" is defined with the prefix "Kilo".

Potence	Name	Symbol	Deutsch	English
10^{24}	Yotta	Y	Quadri-llion	Septi-llion
10^{21}	Zetta	Z	Tri-lliarde	Sexti-llion
10^{18}	Exa	E	Tri-llion	Quinti-llion
10^{15}	Peta	P	Bi-lliarde	Quadri-llion
10^{12}	Tera	T	Bi-llion	Tri-llion
10^{9}	Giga	G	Mi-lliarde	Bi-llion
10^{6}	Mega	M	Mi-llion	Mi-llion
10^{3}	Kilo	k	Tausend	Thousand
10^{2}	Hekto	h	Hundert	Hundred
10^{1}	Deka	da	Zehn	Ten
10^{0}	1		Eins	One
10^{-1}	Dezi	d	1/ 10	
10^{-2}	Zenti	c	1/ 100	
10^{-3}	Milli	m	1/ 1000	
10^{-6}	Mikro	µ	1/ Mi-llion	
10^{-9}	Nano	n	1/ Mi-lliarde	
10^{-12}	Piko	p	1/ Bi-llion	
10^{-15}	Femto	f	1/ Bi-lliarde	
10^{-18}	Atto	a	1/ Tri-llion	
10^{-21}	Zepto	z	1/ Tri-lliarde	
10^{-24}	Yocto	y	1/ Quadri-llion	

10.1.2 Derived quantities and units (selected)

Symbol	Size, Value	Legal unit and SI unit
A	Area	m2 = 0,01a = 0,0001 ha
a	Acceleration	m/s2
B	Induction, magnetic flux density	T [Tesla] = Wb/m²= kg/(s² A)
C	electrical capacity	F [Farad] = C/V = s⁴ A² / (kg m²)
Ek	kinetic energy	J [Joule] = Ws = kg m²/s²
Ep	potential energy	J [Joule] = Ws = kg m²/s²
F	Force	N [Newton] = kg m/s²
G	electrical conductance	S [Siemens] = 1/Ω= A/VC= s³A²/(kg m²)
I	Current	A [Ampere]
L	Inductance	H [Henry] = Wb/A = kg m²/(s²A²)
M	Torque	N m = kg m²/s²
m	Mass	kg
P	Power	W [Watt] = J/s = kg m²/s³
P_N, P_r	Net power, rated Power	W [Watt] = J/s = kg m²/s³
Q	Charge	C [Coulomb] = A s
q	Elementary charge	C [Coulomb]
R	Resistance	Ω [Ohm]=V/A= kg m²/(s³A²)
U	Voltage	V [Volt]= W/A = kg m²/(s³A)
v	Speed	m/s = 3,6 km/h
V	Specific volume	m³/kg
W	Work, energy	J [Joule] = W s = kg m²/s²
ε	Permittivity (dielectric constant)	F/m=A s²/(Vm)=s⁴ A² / (kg m³)
η	Efficiency	-
μ	Permeability	H/m= V s/ (A m) kg m/(s² A²)
φ	Magnetic flux	Wb [Weber]= Vs= kg m² / (A s²)

10.1.3 Relevant parameters for electric ferries/electric ships

kW	Power, product of electrical voltage Volt. Work per time unit.
kWh	capacity and charge of a battery, the stored energy (ability to perform work)
V, Volt	Electrical voltage. The voltage that builds up between two differently electrically charged points.
A, Ampere	Electrical current. SI unit, see there.
C-Wert, C-Faktor	C-factor Charge factor for batteries

10.2 Energy densities

Energy density is a measure of how much energy (in kWh or MJ) is contained in a volume or mass of the substance or system. The higher the energy density, the less mass (weight) of the fuel or battery a vehicle has to carry.

Table: Energy densities of some selected substances or systems

Substance/ System	MJ/kg	kWh/kg	Vs_Diesel	Status	Mode of action
Super-Cap (double layer cond.)	0,01	0,00	0,02%	SotA	Elec
Carbon-zinc battery	0,23	0,06	0,55%	SotA	Chem
NiMH battery	**0,28**	**0,08**	**0,67%**	**SotA**	**Chem**
Li-titanate battery	0,32	0,09	0,76%	SotA	Chem
Alkaline manganese battery	0,45	0,13	1,07%	SotA	Chem
Li-polymer battery	**0,54**	**0,15**	**1,29%**	**SotA**	**Chem**
Lithium sulphur battery	**1,26**	**0,35**	**3,01%**	**R&D**	**Chem**
Lithium air accumulator	**1,60**	**0,44**	**3,82%**	**R&D**	**Chem**
Wood (air-dry)	16,80	4,67	40,10%	SotA	Oxidation
Hard coal	34,00	9,44	81,15%	SotA	Oxidation
Crude oil, petrol, diesel	**41,90**	**11,64**	**100,00%**	**SotA**	**Oxidation**
Methane (Natural Gas)	**50,00**	**13,89**	**119,33%**	**SotA**	**Oxidation**
Hydrogen	120,00	33,33	286,40%	SotA	Oxidation
Radioisotope generator, electric	5000,00	1388,89		SotA	Nuklear
Radioisotope generator, thermic	60000,00	16666,67		SotA	Nuklear

The most important state-of-the-art (SotA) fuels and systems are highlighted.

10.2.1 Energy densities of various power generators

Table: Summary of assumed energy parameters for nuclear and renewable power generation [164]

Energy system	Energy inputs (GWh)	Energy outputs (GWh)	Energy gain ratio	Land-take (km2)	Energy density (GWh/km2)
Nuclear:					
Nuclear: Diffusion	48.040	838.900	17,46	6,49	3233
Nuclear: Centrifuge	14.450	838.900	58,00	6,49	3371
Biomass	83.630.000	893.550.000	10,85	20,05	2,13
Wind:					
Offshore	486.000.000	12.940.000.000	26,63	27,50	22,64
Onshore	29.090.00	901.440.000	30,99	0,05	872,40
Solar PV:					
Solar PV: mc-Si	7155	45.000	6,18	0,00	61,84
Solar PV: pc-Si	12.461	45.000	3,61	0,00	48,86

The most important state-of-the-art (SotA) fuels and systems are highlighted.

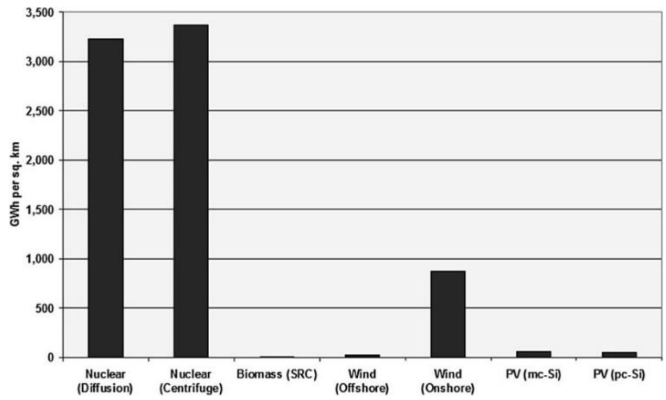


Figure 118 Energy densities of selected power generators.

According to [164], [165], [166], [167].

10.3 Figures on electric mobility

- The growth of motorised private transport has slowed down considerably, but the passenger car remains by far the most important means of transport.
- The shares of public transport and non-motorised transport are increasing slightly.
- The time budget for daily journeys is 80 minutes.
  It has remained roughly the same since the beginning of the studies (1978). The mobility behaviour of people is stable in relation to the amount of time spent.
- The choice of means of transport tends towards motorised individual transport. The distances travelled are increasing.
- The "demographic change" is having an impact on transport. Today's senior citizens are more active than the same age group in earlier generations. Due to their previous transport socialisation, they use the car more often, which leads to a slightly increasing traffic volume.

[43], [168]

Table: Figures on daily private transport (Germany)

		[168]	[43]
		2008	**2017**
Number of daily trips per person		3,4	3,7
Paths, total, daily		162.000.000	
Passenger kilometres, total, daily		2.500.000.000	
Average length of a trail	km	11	12
Average distance per person	km		39
Average length of the working path	km	20,9	
Average travel time	Minutes		20
Average duration for all route	Minutes	80	80
Stock of passenger cars in households	Pass.Cars		43.000.000

10.3.1 How many electric cars are there in Germany?

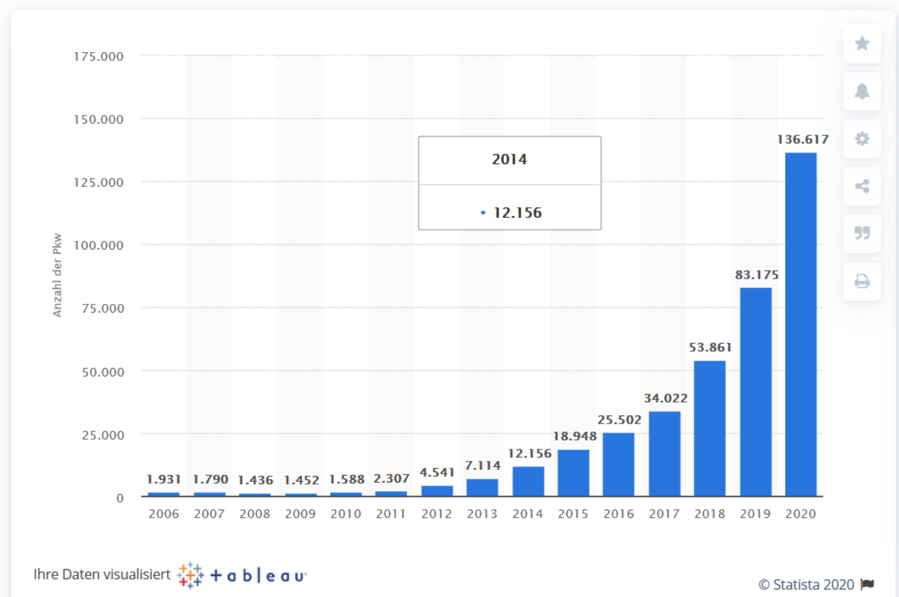


Figure 119 Stock of electric cars in Germany2006 to 2020 [169]

- There are 136617 electric cars in Germany,
- Electric cars are used much less over long distances.
- 64 percent of car trips in everyday traffic are shorter than ten kilometers,
- 95 percent of car trips in everyday traffic are shorter than 50 kilometres and
- only one percent of the trips are longer than 100 kilometres.
- But: 40 percent of car journeys are longer than 50 kilometres.
- Long-distance traffic plays an important role. Range is an important argument and purchase decision.

	Mittlere geschätzte Jahresfahr-leistung	Mittlere Entfernung von Einzel-fahrten	Anteil Einzel-fahrten über 30 km
alle Fahrzeuge	*km*	*km*	*%*
gesamt	**14.700**	**15**	**11**
Benzin	11.800	13	8
Diesel	20.600	20	15
Gas	19.000	19	19
Hybrid	14.000	11	9
Elektro	13.000	12	3

MiD 2017 | Ergebnisbericht | Quelle: MiD 2017

Figure 120 Distance travelled as a function of the type of drive. [43]

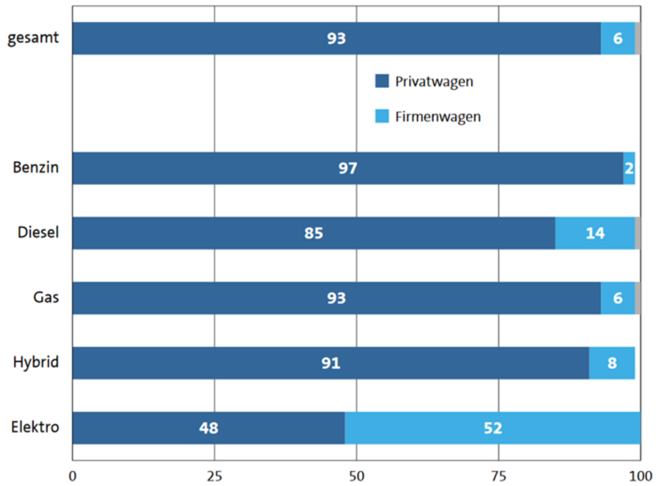


Figure 121 Passenger cars in private households: Three quarters of electric cars continue to have passenger cars in private households. [43]

10.3.2 What is the electricity consumption of electric cars?

Table: How much does electric energy cost for 100 km of travel by car? [170]

Beispiele	**kWh/100km**	
e-Golf	12,7	
Tesla Model S	18,5	
Mean value	**15**	
Price		**4,35 EUR/100km (D: 29 cents/kWh)**

Electricity consumption for electric cars compared to total consumption
(Germany)
Net electricity consumption in Germany in 2019 was around 512 terawatt hours.

Tabelle: Comparison of the electrical energy consumption of e-cars (Germany). [171], [172], [169], [170]

Stock, electric cars (2020)	136.617	Vehicle
Average mileage	10.000	km/year
	1.776.021.000	km/ year
Energy consumption e-car	15	kWh/100km
(Total energy consumption of e-cars)	266.403.150	kWh
Total energy consumption of e-cars	**266,4**	**GWh**
Electrical energy consumption D.	512.000	GWh
Share of electric cars	0,052%	

The current electricity consumption for electric cars accounts for approximately 0.052% of total electric energy consumption. It does not play a role at present.

10.4 Shore power and charging infrastructure for electric ships

Shore connection for cruise ships

Smaller ships in service have supply voltages in the low voltage range (e.g. 400V, 440V, 660V or 1000V and 50Hz or 60Hz). These low voltage levels require large currents at higher power levels. Therefore, future new ships in the cruise sector will be designed for supply voltages in the medium voltage range (11 kV and 50Hz/60 Hz).

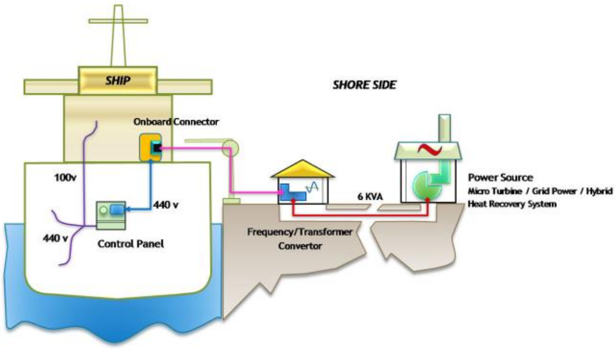


Figure 122 Shore connection, schematic diagram. [173]

With suitable frequency converters, ship networks can be supplied with 11 kV, 6.6 kV / 60 Hz as well as 10 kV, 6.0 kV / 50 Hz. [174]

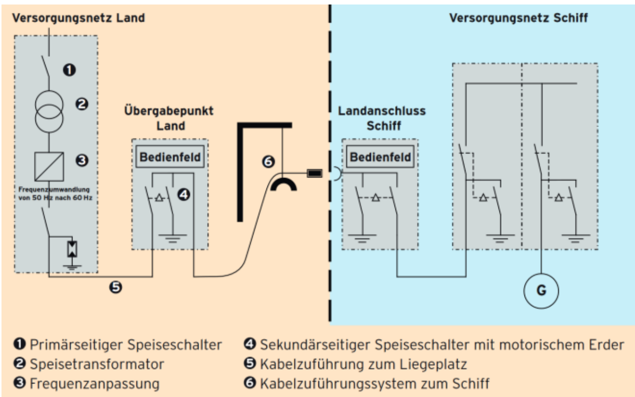


Figure 123 Overview of technical connection components. [174]

How much energy and connected load must be provided?

The figure shows cruise ships of various sizes and the electrical power of the on-board power supply systems.

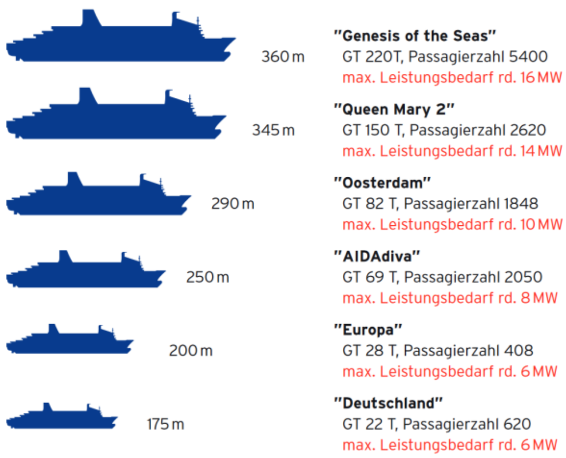


Figure 124 Power requirements of known cruise ships. [174]

The planned shore connection for the cruise ship terminal in Rostock-Warnemünde should have a connected load of 20 MW. The port of Hamburg is designing its shore connection with 14 MW.

For comparison: the city of Rostock with 205,000 inhabitants has a peak grid capacity of 130 MW (between 90 and 130 MW).

10.4.1 Vogelflug-Linie (Puttgarden-Rødby)

The ferry company Scandlines has ideas for a project to electrify the Vogelfluglinie between Puttgarden and Rødby. The plan is to use battery-powered vessels (retrofit to electric propulsion).

According the timetable the line operates one departure every 40 minutes from each side, served by three ships (M/F Deutschland, M/F Schleswig-Holstein and M/F Prinsesse Benedikte). That is 36 crossings from each port, 72 crossings in total. Each ship makes 24 crossings and is therefore in operation around the clock. The crossing takes 45 minutes, the berthing time in the port is 15 minutes. Loading must take place during the berthing time. [175]

The energy for one crossing is 4 MWh. What power must the charging infrastructure be designed for? What challenges have to be overcome?

The following parameters have been researched and calculated, based on: [176]

Energy consumption for one crossing	**W=**	**4**	**MWh**
Mooring time in port (Puttgarden or Rødby)		12	Minutes
Charging time	t=	0,20	Hours
Power (P = W / t) of the charging infrastructure	**P=**	**20**	**MW**

The charging infrastructure for recharging must be designed with a capacity of 20 MW. Such a recharging infrastructure does not yet exist.

table: More relevant facts about the ferry line

Number of crossings per day	72	every 40 minutes from each side
Distance of a crossing	19	Km
Energy consumption per trip and ship	4	MWh
Energy consumption for the crossings per day	**288**	**MWh**

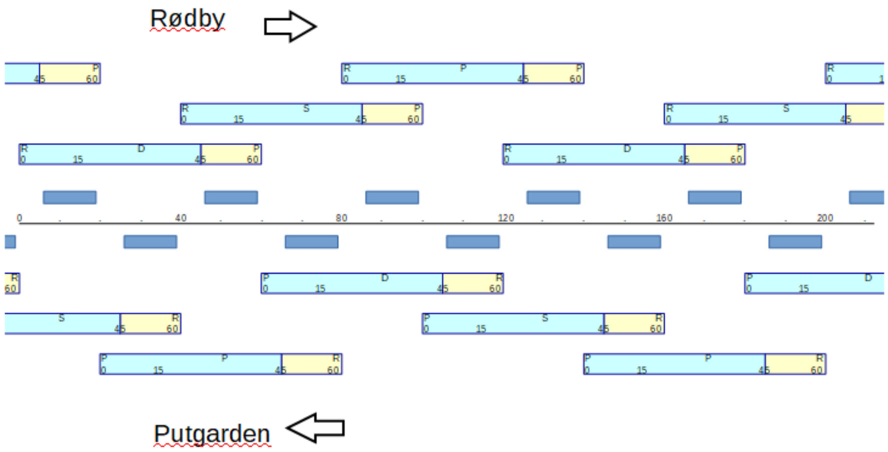


Figure 125 Scheme of circulation and loading activities in Rødby und Putgarden. [177]

Ships: D= „Deutschland", S= „Schleswig-Holstein, P= „Prinsesse Benedikte"

The loading stations in the ports are operated with a 25-minute interruption.
In addition to the large capacity, the energy supply of 288 MWh is likely to pose a further challenge. However, with an average daily per capita consumption of 4.532 kWh (1,654 kWh/year), 288 MWh corresponds to a city with around 63,000 inhabitants. [178]

Table: Comparison of charging systems and their performance for electric cars and electric ferries (M/F "Ampere" and project "Vogelfluglinie"). Own calculations with the help of [179]

System	Type	Voltage	Amperage	Power	Charging time	Energy
		(V)	(A)	(kW)	(h)*	(kWh)
"Schuko"	2-phase AC	230	10	2	17,0	39
Wallbox Typ2 normal	2-phase AC	230	20	5	9,0	41
Wallbox Typ2 schnell	3-phase AC	400	32	22	2,0	44
M/F "Ampere"	**DC**	**1.000**	**1.250**	**1.250**	**0,2**	**250**
"Vogelfluglinie"	**3-phase AC**	**11.000**	**1.100**	**20.958**	**0,2**	**4.192**

* Approximate value

In order to be able to establish a contact in a meaningful way at such high power levels, the current must be kept within reasonable limits. This can only be achieved by increasing the voltage, as is planned for the new shore connections for cruise ships, which are designed for voltages of 11 kV (11,000 V). Nevertheless, currents of approx. 1100 amperes are required.

This can only be achieved if the voltage is increased, as is planned for the new shore connections for cruise ships, with voltages of 11kV (11,000 V). Nevertheless, currents of approx. 1100 amperes are required.
For comparison: The M/F "ampere" is charged with direct current. The electrical connection is made with the help of a pantograph, which according to the manufacturer is already a challenge due to the high currents (up to 1250 amperes). The provision of a charging capacity of 1.25 MW on both sides of the crossing has already been reported on in the section "Examples".

10.5 What do fuel cells cost?

Why are fuel cells expensive? What are the cost drivers of fuel cells?

10.5.1 Construction

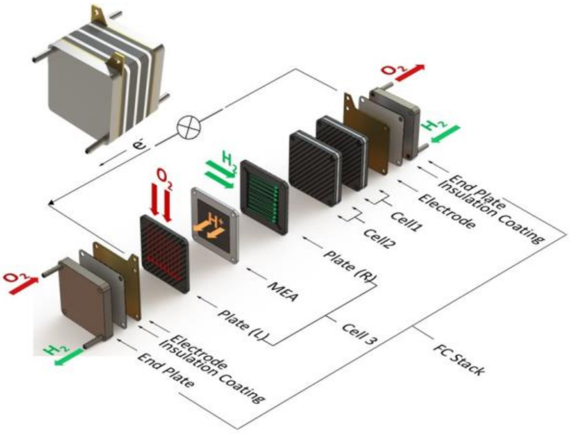


Figure 126 Exploded view of a fuel cell. [180]

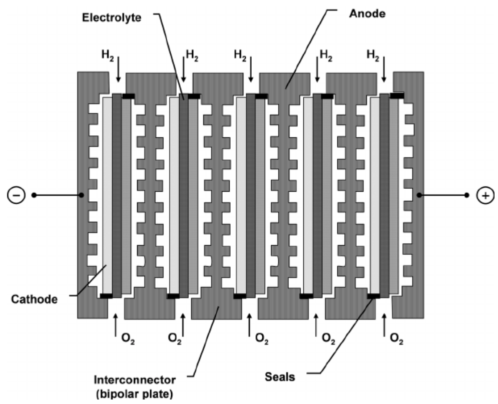


Figure 127 Schematic diagram of a fuel cell stack. [181]

Scheme: Basic structure and components

System	Stack	Cell 1	MEA	Fuel / Pol
Periphery				
	Endplate			
	Cell 1	Isolator		
		Electrode		**(+) Pol**
		Plate		← O2
			MEA	
		Plate		← H2
		Electrode		(-) Pol
	Cell 2			
	. . .			
	Cell n			
	Electrode			**(-) Pol**
	Isolator			
	Endplate			
Periphery				

10.5.2 MEA for Fuel cells

The MEA (membrane electrode assemblies) is the most important active component of a fuel cell.

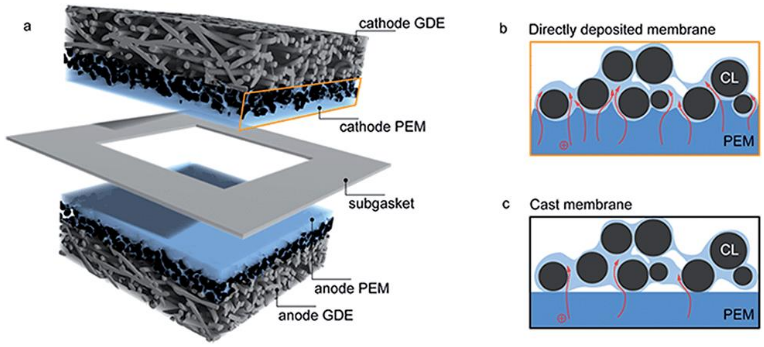


Figure 128 Diagram of a MEA. [182]

Explanation of the illustration:

a) A thin PEM layer is printed directly on anode and cathode gas diffusion electrodes with ink jet. A thin under-seal prevents the transfer of hydrogen and current through the end faces of the active area.
b) The dispersed polymer electrolyte (dark blue) can easily adapt to the catalyst layer surface, resulting in relatively thin membranes and an increased electrolyte contact area of the membrane and the ionomer phase of the catalyst layer (light blue).
c) This promotes higher proton conductivity (indicated by red arrows) without affecting fuel crossing. This effect is not as pronounced with conventional MEAs using cast membranes. [182]

The membrane electrode assembly (MEA) is a combination of proton exchange membranes, catalysts and electrodes. On the anode side, a fuel (hydrogen, methanol, etc.) diffuses through the membrane and is met at the cathode end by an oxidant (oxygen or air) which combines with the fuel and absorbs the electrons separated from the fuel. Catalysts on each side enable reactions. The membrane separates the gases/media from each other but is permeable to the protons. In this way the cell potential is maintained and electric current can be drawn from the cell. [183]

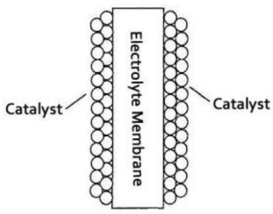


Figure 129 MEA Prinziple. [183]

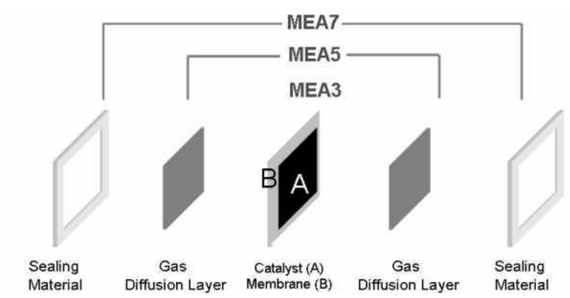


Figure 130 MEA – Layer structure. [183]

Three types of MEA are common: 3-layer MEA, 5-layer MEA, 7-layer MEA.

3-layer MEA:

- ...membrane, about 50 microns thick,
- active layer with Pt catalyst on both sides, the anode and cathode side,
- Catalyst loading: 70% Pt / C,
- Sizes of the active surface: 5, 16, 25, 50, 100 cm^2.

5-layer MEA:

- Same as 3-layer MEA, but additionally on both sides:
- Gas fleece diffusion layer with microporous layer.

7-layer MEA:

- Like 3-layer MEA, additionally on both sides:
- Gas diffusion layers and seal (silicone flat seal).

10.5.3 Price calculation of an example fuel cell

1. Price example for a MEA

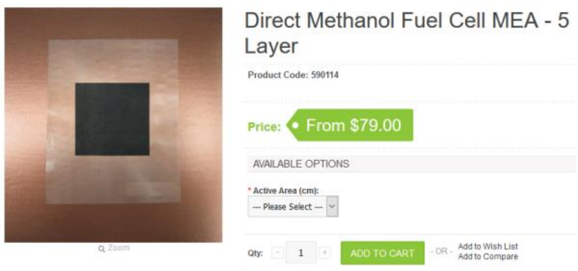


Figure 131 Price quotation for a DMFC MEA-5 for low power applications: 79 USD. [184]

2. MEA properties [184]

MEA Type	Direct Methanol Fuel Cell (DMFC)
Membrane Type	Nafion™ 117
Membrane Thickness	183 micrometers (7.2 mil)
Anode Loading	4.0 mg/cm^2
Anode Catalyst	Platinum Ruthenium
Cathode Loading	4.0 mg/cm^2
Cathode Catalyst	Platinum Black
Gas Diffusion Layer	Carbon Cloth with MPL - W1S1010
Gas Diffusion Layer Type	Woven Carbon Fiber Cloth
Gas Diffusion Layer Thickness	0,365 mm (365 microns)

3. Examples of complete fuel cell systems for comparison (Alibaba (FC), 2020)

Ref.	Item (Alibaba.com)	P(W)	U(V)	M (kg)	V (mm3)	Preis (USD)
Ref.1	PEM Fuel Cell Active Stack / Water cooling	335	28 - 40	1,8	90x140x75	**8.000**
Ref.2	PEMFC Hydrogen Powered Fuel Cell 1500w for Motorcycle battery	1500	33 - 55	1.6	260X145X200	**14.000**
Ref.3	PEM Fuel Cell Active Stack / Air cool-ing	350	24 - 40	1,26	90x205x107	**7.200**


Figure 132 Fuel cell: Ref.1 [185]


Figure 133 Fuel cell: Ref.2


Figure 134 Fuel cell: Ref.3

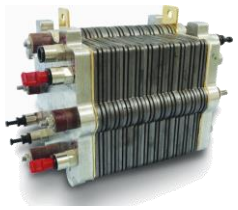


Figure 135 Example FC [185]

4. A „Replica“ of a Fuel cell for price estimation

Voltage, current and performance of a MEA [183]	U= I= P=	0,65V 1 A / cm²; 0,65 W/cm²
Area of the MEA [184]	A=	5x5 cm² = 25cm²
Power of the MEA [183]	P=	25cm² * 0,65 W/cm² = 16,25 W
Amperage of the MEA	I=	25 A

5. Example: Ref 1 [185], 335 W

How many MEAs are needed (cost)?

	Example Ref 1 [185]	**„Replica“ mit 25cm² MEA**
Voltage, U	28 - 40 V	30V / 0,65V = 46 MEA 40V / 0,65V = 62 MEA
Quantity MEA	k. A.	46 MEA * 0,65V = 29V 62 MEA * 0,65V = 40,3V
Power, P	335 W	46 MEA * 16,25W = 747,5 W 62 MEA * 16,25W = 1.007,5 W
Cost (MEA)	8.000 USD for the complete system	46 x 79 EUR = 3.634 EUR 62 x 79 EUR = **4.898 EUR**

Around EUR 5,000 for the MEA and around EUR 5,000 for the "rest"= EUR 10,000 is roughly the cost of this fuel cell configuration. (approx. 1,000 EUR/ kW)

Price estimations in the older literature

Older literature still contained optimistic statements: [186]

- 1990: $5,000/kW
- 1998: $500/kW
- Target: $25-$30/kW

In addition, an estimate of the costs per kilowatt of the individual fuel cell components (in USD/kW) for 1999 / 2010 was made. The percentage distribution of the costs was added by us.

Table: Price distribution among fuel cell components

Component	1999	2010	percent. 1999	percent. 2010
Platinum catalyst	65	6	28%	30%
Polymer-Membran	70	10	30%	50%
Plates	80	2	35%	10%
Other	15	2	7%	10%
Total	230	20	100%	100%

It turns out that the estimates did not occur in this way. Fuel cell systems are still more expensive than 20 USD/kW.

11 References

[1] Viziv, „Power Delivery Without Wires," Viziv Inc., 2018. [Online]. Available: https://vizivtechnologies.com/science/utilizations/energy/.

[2] Z. Brzezinski, „America in the Technetronic Age," *Childhood Education, Vol 45, 1*, pp. 6-10, 1968.

[3] Z. Brzezinski, BETWEEN TWO AGES - America's Role in the Technetronic Era, NEW YORK: THE VIKING PRESS, 1970.

[4] D. Meadows und et.al., Die Grenzen des Wachstums. Bericht des Club of Rome zur Lage der Menschheit, Stuttgart, 1972.

[5] UNO, „UN World Population Prospects," 2020. [Online]. Available: https://esa.un.org/unpd/wpp/.

[6] ZSW-BW, „Zahl der Elektroautos steigt weltweit von 5,6 auf 7,9 Millionen," 2019. [Online]. Available: https://www.zsw-bw.de/presse/aktuelles/detailansicht/news/detail/News/zahl-der-elektroautos-steigt-weltweit-von-56-auf-79-millionen.html.

[7] A. John, Artist, *Mapping möglicher Potentiale zur Elektrifizierung von Fähren.* [Art]. Eigenes Werk, unter Nutzung von My_Maps (Google), 2020.

[8] Wikipedia Fähre , „Fähre - Ferry," 2020. [Online]. Available: https://de.wikipedia.org/wiki/F%C3%A4hre. [Zugriff am 2020].

[9] A. John, Artist, *Die Fähre über die Saale bei Wettin. Führungskette einer Fähre..* [Art]. Eigenes Werk, 2020.

[10] A. John, Artist, *Die Fähre über die Saale bei Wettin.* [Art]. Eigenes Werk, 2020.

[11] W. Eggebrecht und P. Danker-Carstensen, „Fährschiffahrt in Mecklenburg-Vorpommern - Ein Forschungsbericht," in *Deutsches Schiffahrtsarchiv*, Deutsches Schiffahrtsarchiv, 1996.

[12] A. Kunst, „Verkehr & Logistik - Schifffahrt - Sind Sie in den letzten 2 Jahren auf einer Fähre gefahren?," 06 11 2019. [Online]. Available: https://de.statista.com/statistik/daten/studie/681448/umfrage/umfrage-in-deutschland-zur-nutzung-von-faehren-in-den-letzten-2-jahren/.

[13] Ruter, „Helelektrisk overfart på Norges største bilfrie båtsamband," 07 05 2020. [Online]. Available: www.mynewsdesk.com/no/ruter/pressreleases/helelektrisk-overfart-paa-norges-stoerste-bilfrie-baatsamband-2996757. [Zugriff am 2020].

[14] A. John, Artist, *Übersetzen mit der Fähre "Föri" über den Fluss Aurajoki..* [Art]. Eigenes Werk, 2018.

[15] A. John, Artist, *Übersetzen zu Fuß über den Fluss Aurajoki im Winter..* [Art]. Eigenes Werk, 2018.

[16] IPCC , „Intergovernmental Panel on Climate Change,," 2019. [Online]. Available: www.ipcc.ch.

[17] UNFCCC/FCCC, „United Nations Framework Convention on Climate Change (UNFCCC/FCCC), international environmental treaty," 1992. [Online]. Available: https://unfccc.int/process-and-meetings/the-convention/status-of-ratification/status-of-ratification-of-the-convention.

[18] Navionics, „Navionics Charts," 05 2020. [Online]. Available: www.navionics.com/deu/charts/.

[19] N. N., Artist, *Dampffähre über die Warnow.* [Art]. bearbeitet nach einer alten Bildpostkarte, 2020.

[20] FjordFähren, „Fotogalerie und technische Daten," 2020. [Online]. Available: http://www.fjordfaehren.de/d/d_meckpom.htm.

[21] N.N., Artist, *Fährschiff "Willi Schröder".* [Art]. ca. 1980.

[22] Karnitzki, Artist, *Fährbetrieb mit der "Albert Schmidt".* [Art]. Bundesarchiv, 1963.

[23] N. N., Artist, *Fährboot nach Gehlsdorf, ca. 1970er Jahre..* [Art]. Internet, 1970.

[24] A. John, Artist, *Die Fähre „Gehlsdorf"am Anleger.* [Art]. Eigenes Werk, 2019.

[25] Vergabe24, „Wettbewerblicher Dialog," 2020. [Online]. Available: https://www.vergabe24.de/vergaberecht/vergabelexikon/wettbewerblicher-dialog/.

[26] GWB, „Gesetz gegen Wettbewerbsbeschränkungen (GWB)," 2020. [Online]. Available: https://www.gesetze-im-internet.de/gwb/___119.html.

[27] Business Europa, „Regeln für die Vergabe öffentlicher Aufträge," 2020. [Online]. Available: https://europa.eu/youreurope/business/selling-in-eu/public-contracts/public-tendering-rules/index_de.htm#thresholds.

[28] Y. Bakkar, „Enhancing business potential through enterprises in EU-funded projects," Tallinn, 2019.

[29] EIHA, „The European Investment Advisory Hub," 2020. [Online]. Available: https://eiah.eib.org/.

[30] WSV.de, „ELWIS," 15 05 2020. [Online]. Available: https://www.elwis.de/DE/Service/Foerderprogramme/Foerderprogramme-node.html.

[31] H. Arndt, „Doppelend-Auto-/Personenfähre mit vollelektrischem Antriebskonzept - Potenzialanalyse & technische Machbarkeits-/ Konzeptstudie," Neptun Ship Design GmbH, Rostock, 2018.

[32] N. Shipdesign, Artist, *Warnow-Hopper. Doppelend-Personenfähre mit vollelektrischem Antriebskonzept..* [Art]. Computersimulation, eigenes Werk, 2018.

[33] A. John, Artist, *Wellenartige Überlagerung von Wachstumsvorgängen.* [Art]. Eigene Darstellung in Anlehnung an Wachstums- und Produktionsfunktionen sowie die sog. Gartner-Hypecycles, 2020.

[34] Wikipedia Kondratjew-Zyklus, „Kondratjew-Zyklus," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Kondratjew-Zyklus.

[35] FKT, Artist, *Wechsel der Logik des sozialen Verhaltens als Folge der verschiedenen Periodizität der biologischen und technogenen Zeit..* [Art]. nach Фонд Концептуальных Технологий Altai, 2020.

[36] Zukunftsinstitut, „Megatrend Urbanisierung," 2020. [Online]. Available: https://www.zukunftsinstitut.de/dossier/megatrend-urbanisierung/.

[37] Urbanisierung, „Urbanisierung," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Urbanisierung.

[38] LBBW, „Urbanisierung–Demographische Entwicklungen und Auswirkungen im globalen Vergleich," 08 2015. [Online]. Available: https://www.lbbw.de/public/research/blickpunkt/20150817_lbbw___blickpunkt_urbanisierung_demographische_entwicklungen_und_auswirkungen_7x7zfd8or_m.pdf.

[39] J. Bähr, „Ursachen von Urbanisierung," 2008. [Online]. Available: https://www.berlin-institut.org/online-handbuchdemografie/bevoelkerungsdynamik/auswirkungen/ursachen-von-urbanisierung.html.

[40] Wikipedia Urban, „Urbanisierung," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Urbanisierung.

[41] Wikipedia Theelacht, „Theelacht zu Norden," 2020. [Online]. Available: www.wikipedia.org. [Zugriff am 2020].

[42] S. Heng, „Sharing Economy - Teile und profitiere," *PT-Magazin für Wirtschaft und Gesellschaft,* Bd. 16. Jahrgang, Nr. Ausgabe 3-4, 2020.

[43] infas, „Mobilität in Deutschland - MiD -- Ergebnisbericht," infas Institut für angewandte Sozialwissenschaft GmbH , Bonn, 2019.

[44] Zukunftsinstitut, „Urbanisierung: Die Stadt von morgen," 2020. [Online]. Available: https://www.zukunftsinstitut.de/artikel/urbanisierung-die-stadt-von-morgen/.

[45] G. Agricola, De re metallica libri XII, quibus officia, instrumenta, machinae, ac omnia denique ad metallicam spectantia, describuntur, Basel: Emanuel König, 1657.

[46] G. Agricola, Artist, *Early mine wagon (German: "Leitnagel-Hund") running on wooden rails..* [Art]. wikimedia.org; File:Leitnagel Hund (Mining cart).png, (1494–1555).

[47] W. Behringer, Artist, *Eisenbahn gegen Postkutsche. Spottbild auf die Eisenbahn..* [Art]. Scan aus Wolfgang Behringer: Thurn und Taxis. Piper, München 1990, nach S. 336, 1835.

[48] P. P. Dahms, „Die Anfänge des Personenverkehrs per Eisenbahn in Preußen 1835-1860," Fakultät Geisteswissenschaften der Technischen Universität Berlin; 14. Juli 2015, Berlin, 2015.

[49] R. Rossberg, Geschichte der Eisenbahn, Künzelsau: Sigloch-Edition, 1977.

[50] Wikipedia Erdöl, „Erdöl," 2019. [Online]. Available: https://de.wikipedia.org/wiki/Erd%C3%B6l. [Zugriff am 2020].

[51] W. E. Ayrton, Practical Electricity: A Laboratory and Lecture-course for First Year Students of Electrical Engineering, Based on the Practical Definitions of the Electrical Units, University of Michigan: Cassell, 1891 .

[52] Wiki-Voltaic_Pile, „Volta Säule," 2020. [Online]. Available: wikipedia.org/wiki/Voltaic_pile.

[53] Wikipedia E-Boot, „Jacobi-Boot," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Jacobi-Boot.

[54] K. Iwatate, Artist, *Slaby-Beringer Elektrowagen, 1920.* [Art].

[55] O. Selchow, Artist, *Elektroautos am Charlottenburger Ufer (nahe der Fabrik). Die Bestellung ging nach Japan..* [Art].

[56] E. H. Wakefield, History of the Electric Automobile: Battery-Only Powered Cars, Society of Automotive Engineers,U.S. (1. Mai 1994), 1994.

[57] Guinness, The Guinness Books Of Cars, Facts & Feats, Bd. Third Edition, Norwich: ISBN 0-85112-207-8, 1980, p. S. 28.

[58] P. Maxwill, „Elektroauto-Revolution 1912," 11 06 2012. [Online]. Available: https://www.spiegel.de/geschichte/elektroauto-revolution-vor-100-jahren-a-947600.html.

[59] RSAG, „Geschichte der Rostocker Straßenbahn," 2020. [Online]. Available: www.rsag-online.de.

[60] Wikipedia U-Bahn, „Geschichte der Berliner U-Bahn," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Geschichte_der_Berliner_U-Bahn.

[61] Wiki Subway, „New York City Subway," 2020. [Online]. Available: https://de.wikipedia.org/wiki/New_York_City_Subway.

[62] Wikipedia Ottomotor, „Ottomotor," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Ottomotor.

[63] Wikipedia Benz, „Benz Patent-Motorwagen Nummer 1," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Benz_Patent-Motorwagen_Nummer_1.

[64] J. Paeger, „Eine kleine Geschichte des Erdöls," 2006 – 2019. [Online]. Available: www.oekosystem-erde.de/html/geschichte_erdoel.html. [Zugriff am 2020].

[65] E. Kettelhut, Artist, *Szenenbild für den Film „Metropolis" von Fritz Lang. (Stadt und Mobilität der Zukunft).* [Art]. Deutsche Kinemathek Berlin, 1927 .

[66] J. W. v. Goethe, Faust. Der Tragödie zweiter Teil.

[67] G. Buttkewitz, Artist, *Prinzipdarstellung eines Elektro-Antriebes.* [Art]. Eigenes Werk, 2020.

[68] Wkipedia (Prop), „Siemens AG - C (Siemens agreed the publication at de: Bild: Siemens Schottel Propulsor.jpg),“ 2020. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=397859. [Zugriff am 2020].

[69] ABB, Artist, *ABBs Elektroantrieb Azipod® kann jährlich Treibstoffkosten in Höhe von 1,7 Millionen US-Dollar sparen.* [Art]. Media Relations, media.relations@ch.abb.com, 2019 .

[70] G. Buttkewitz, Artist, *Struktur eines Batteriesystems und Ladegerät.* [Art]. Eigenes Werk, 2020.

[71] Galvani, „Archive Org,“ 2019. [Online]. Available: https://archive.org/details/AloysiiGalvaniD00Galv/page/58/mode/2up.

[72] Volta, „Amazon,“ 2020. [Online]. Available: https://www.amazon.com/Clementoni-61274-Voltaic-Pile-Toy/dp/B01H7HJW6Q.

[73] Wikipedia GalvCell, „A common example of a galvanic cell, labeled. Galvanische_Zelle,“ 2019. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=17902682.

[74] Wikipedia, Akkutypen, „wikipedia.org,“ 2020. [Online]. Available: https://de.wikipedia.org/wiki/Akkumulator#Akkumulatortypen.

[75] Wikipedia (C-Faktor), „Wikipedia.org,“ 2020. [Online]. Available: https://de.wikipedia.org/wiki/Kapazit%C3%A4t_(galvanische_Zelle)#C-Faktor.

[76] Wikipedia. Li-Ion-Akku, „wikipedia.org,“ 2020. [Online]. Available: https://de.wikipedia.org/wiki/Lithium-Ionen-Akkumulator.

[77] C. Deinhardt, „Feuergefahr bei Lithium-Ionen-Akkus Was tun bei Batteriebrand?,“ 23 01 2020. [Online]. Available: www.elektroniknet.de/elektronik/power/was-tun-bei-batteriebrand-171926.html.

[78] A. John, Artist, *Batterieraum der MV "Elektra". Lithium-Ionen-Batteriesysstem von 500 kWh..* [Art]. Eigenes Werk, 2018.

[79] Wikipedia: Ladeverfahren, „wikipedia.org,“ 2020. [Online]. Available: https://de.wikipedia.org/wiki/Ladeverfahren.

[80] J. Kunkelmann, „Untersuchung des Brandverhaltens von Lithium-Ionen- und Lithium-Metall-Batterien in verschiedenen Anwendungen und Ableitung einsatztaktischer Empfehlungen,“ KIT Bericht Nr. 175,, Karlsruhe, 2016.

[81] H. Lemme, „Das zweite Leben das Akkus,“ *Elektronik, Nr. 5* , p. S. 38., 2019.

[82] S. Bruns und M. Dinse, „Brandschutz im Umgang mit gebrauchten Lithium-Ionen-Batterien im Recyclingbetrieb.,“ 2020. [Online]. Available: http://www.stoebich-technology.de.

[83] G. Buttkewitz, Artist, *Prinzp eines Brennstoffzellensystems.* [Art]. Eigenes Werk, 2020.

[84] A. John, Artist, *Aufbau einer Brennstoffzelle und Erläuterungen..* [Art]. basierend auf einer Darstellung von Wikipedia, 2020.

[85] G. Buttkewitz, Artist, *Brennstoffzellen-Stack auf dem Prüfstand.* [Art]. Eigenes Werk, 2011.

[86] P. Pioch, T. Aigle und L. Jörissen, „Basisseminar Brennstoffzellen- und Wasserstofftechnologie," WBZU, Ulm, 2008.

[87] Wikipedia SOFC, „Wikipedia.org," 2020. [Online]. Available: https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell.

[88] Wikipedia PEMFC, „Wikipedia.org," 2020. [Online]. Available: https://en.wikipedia.org/wiki/Proton-exchange_membrane_fuel_cell.

[89] Green Car Congress, „ZAP and Apollo Demo On-Board Ammonia Reformer for Alkaline Fuel Cell Car," 2005. [Online]. Available: https://www.greencarcongress.com/2005/05/zap_and_apollo_.html.

[90] T. Kuther, „Elektronik Praxis," 26 05 2015. [Online]. Available: https://www.elektronikpraxis.vogel.de/100-kilowatt-brennstoffzelle-fuer-autos-im-dauertest-a-490317/.

[91] G. Schiller, „Überblick über die Verfahren der Wasserelektrolyse und Forschungsergebnisse sowie Forschungsbedarf bei der alkalischen Elektrolyse,," *34. Ulmer Gespräche Energiesys-teme der Zukunft, 3.-4. Mai 2012,* 2012.

[92] Wikipedia Reforming, „Dampfreformierung," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Dampfreformierung.

[93] Daimler_AG, Artist, *Druckwasserstoffspeicher bei 300 bar, Quelle: Daimler AG.* [Art]. Daimler AG.

[94] Quantum, Artist, *Druckwasserstoffspeicher bei 700 bar.* [Art]. Quantum Technologies.

[95] Linde, Artist, *Speicherung von füssigem Wasserstoff.* [Art]. Linde AG.

[96] Wikipedia Metallhydrid, „Wikipedia.org," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Metallhydridspeicher.

[97] Daimler_AG, Artist, *Metallhydridspeicher für Wasserstoff.* [Art]. Daimler AG.

[98] Wikipedia LOHC, „Wikipedia.org," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Fl%C3%BCssige_organische_Wasserstofftr%C3%A4ger.

[99] K. Müller, Artist, *Schema einer Energiespeicherung mittels chemischer Speicherung von Wasserstoff auf einem organischen Wasserstoffträger (LOHC).* [Art]. Bayrisches Wasserstoff Zentrum, 2012.

[100] e-mobil BW GmbH, „Wassersstoff-Infrastruktur für eine nachhaltige Mobilität," e-mobil BW GmbH – Landesagentur für Elektromobilität und Brennstoffzellentechnologie, Baden-Württemberg, Ministerien für Finanzen und Wirtschaft; Verkehr und Infrastruktur; Umwelt, Klima und Energiewirtschaft., 2013.

[101] Linde, Artist, *Shell-Tankstelle in Berlin Sachsendamm..* [Art]. Linde AG.

[102] G. Buttkewitz, Artist, *Prinzip der Elektroenergieerzeugung mittels Wärmekraftmaschinen..* [Art]. Eigenes Werk, 2020.

[103] IAEA, „INIS international Nuclear Information System," 2020. [Online]. Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:31018687.

[104] Wikipedia 4GR, „Generation IV reactor," 2020. [Online]. Available: https://en.wikipedia.org/wiki/Generation_IV_reactor.

[105] Wikipedia RangeExtender, „Range Extender, Reichweitenverlängerer," 2020. [Online]. Available: https://de.wikipedia.org/wiki/Reichweitenverl%C3%A4ngerer.

[106] I. Schillinger, „Solar-Elektrische Fähren und Personenschiffe," OstseestaalGmbH & Co.KG AmpereshipGmbH, Stralsund, 2018.

[107] Henschke Werner und Autorenkollektiv, Schiffbautechnisches Handbuch. Band 1-3 SCHIFFBAU [Schiffstheorie; Widerstand, Vortrieb und Steuern; Schiffsfestigkeit; Werkstoffe; Schweißung im Schiffbau; Klassifizierung und Bauvorschriften; Normung; Schiffsentwurf, Schiffbauliche Einrichtungen], 1957.

[108] C. F. Mayer und R. S. Marquardt, Schiffstechnik und Schiffbautechnologie, Hamburg: Seehafen-Verlag ISBN 978-3-87743-817-6, 2006.

[109] 11. Automatisierungstreff in Böblingen, „Kompakt - Lotsenboot mit elektrischem Antrieb Schiffbau & Offshore-Technologie," *Schiff & Hafen, Fachzeitschrift für Schifffahrt,* 2018.

[110] Jahrbücher der Schiffbautechnischen Gesellschaft, Schiffshydrodynamik, Hamburg: Schiffahrts-Verl. Hansa, 1900 89(1995, ff.).

[111] Hansa, „Pod drives/rim thrusters survey 2018," *Hansa, im Schiffahrts-Verlag Hamburg, 155 (2018) 5 Mai,* pp. 66-68, 05 Mai 2018.

[112] R. Prof. Dr. Bronsart, Glossar Schiffstechnik, Hamburg: Seehafen Verlag, DVV Media Group, 2016.

[113] ESTS, „Emerging technologies for future electric ships," in *Symposium, IEEE Electric Ship Technologies*, Westin Crystal City Hotel, Arlington, VA / Institute of Electrical and Electronics Engineers. - [Piscataway, NJ] : IEEE, 2019, 2019, August 14-16 .

[114] P. D. G. Schmitz, Hydrodynamik und Anwendung auf Schiffe, Rostock: Universität Rostock, 1978.

[115] Ostseestaal, Artist, *Elektro-Fähr- und Fahrgastschiffe.* [Art]. Ostseestaal GmbH, 2015.

[116] B. Aa, Artist, *Future of the Fjords: Elektrofähre in Norwegen.* [Art]. Auto Motor Sport, 2020.

[117] A. John, Artist, *Future of the Fjords.* [Art]. Eigenes Werk, 2019.

[118] FacilityM, „Strategische Instandhaltung von Gebäuden," bauverlag.de, 2008. [Online]. Available: https://www.facility-

management.de/artikel/fm__Strategische__Instandhaltung__von__Gebaeuden__53902.html. [Zugriff am 2020].

[119] Vogel, „Instandhaltungsstrategien im Überblick," Vogel Communications Group; www.vogel.de , 2020 . [Online]. Available: https://www.bigdata-insider.de/vorausschauende-instandhaltung-per-intelligenter-datenanalyse-gal-498451/. [Zugriff am 2020].

[120] i-care, „Vorausschauende Instandhaltung," I-Care Deutschland GmbH , 2014. [Online]. Available: https://www.i-care-deutschland.de/2014/10/20/vorausschauende-instandhaltung/. [Zugriff am 2020].

[121] NautiTronix, Artist, *Symbolbild.* [Art]. NautiTronix UG, 2019.

[122] WF, Artist, *Ferndiagnosesystem: Visualisierung von Daten.* [Art]. Weiße Flotte GmbH, 2019.

[123] I. Schillinger, „Aktuelle Entwicklungen in der Elektromobilität in der Berufsschifffahrt am Beispiel von realisierten Projekten," Leipzig, 2018.

[124] D. Hastert, Artist, *Stop vun der neier Musel-Fähr SANKTA MARIA II zu Oberbillig de 25.11.2017.* [Art]. Wikimedia Commons, 2017.

[125] Wikipedia Ampere, „Ampere (Schiff)," 2013. [Online]. Available: https://de.wikipedia.org/wiki/Ampere_(Schiff). [Zugriff am 2020].

[126] ingenieur.de, „Weltweit erste Elektrofähre in Norwegen im Einsatz," 20 05 2015. [Online]. Available: https://www.ingenieur.de/technik/fachbereiche/e-mobilitaet/weltweit-elektrofaehre-in-norwegen-im-einsatz/. [Zugriff am 2020].

[127] Wikimalte, Artist, *Fähre "Ampere" (Baujahr 2014) mit Elektroantrieb auf dem Sognefjord, nahe Lavik.* [Art]. Wikimedia Commons, 2017.

[128] Corvus, „The world's first all-electric car ferry," 2014 . [Online]. Available: https://corvusenergy.com/projects/mf-ampere/. [Zugriff am 2020].

[129] Corvus, „CASE STUDY: Norled AS, MF Ampere, Ferry," Corvus Energy, Bergen, 2015.

[130] Wikipedia Ellen , „Ellen (Schiff)," 2019. [Online]. Available: https://de.wikipedia.org/wiki/Ellen_(Schiff). [Zugriff am 2020].

[131] E. Christensen, Artist, *Since 15-08 2019 operated Ærø Municipality with the E-ferry Ellen between the southern danish ports of Fynshav to Søby, on the island of Ærø, Denmark..* [Art]. Wikimedia Commons, 2019.

[132] E. Christensen, Artist, *E-ferry Ellen (Danish: Elfærgen Ellen) is a pioneering electric car ferry with 4.3 MWh battery system.* [Art]. Wikimedia Commons, 2020.

[133] A. John, Artist, *Die Route der Elektrofähjre "Ellen".* [Art]. Eigenes Werk auf Basis von myMaps/ Google Maps, 2020.

[134] P. Pospiech, „Ærø-Windmühlen elektrifizieren E-Fähre ELLEN," 3 10 2019. [Online]. Available: http://www.veus-shipping.com/2019/10/aero-windmuehlen-elektrifizieren-e-faehre-ellen/. [Zugriff am 2020].

[135] Aerofaergerne, „E/F Ellen," !% 08 2019 . [Online]. [Zugriff am 2020].

[136] Zemship Projekt, „100 Fahrgäste und null Emissionen - Das erste Fahrgastschiff mit Brennstoffzellenantrieb," Karim-Tarik Hammou, hySOLUTIONS GmbH, Hamburg, 2010.

[137] LIFE06, „ZEMSHIPS – ZERO-EMISSION SHIPS," Laienbericht LIFE06 ENV/DE/465 , Hamburg, 2010 .

[138] Innogy, Artist, *MF "Innogy" - greenfuel" ist Leuchtturmprojekt der Grünen Hauptstadt.* [Art]. Innogy / RWE, 2018.

[139] Wikipedia Innogy , „Innogy (Schiff)," 2018. [Online]. Available: https://de.wikipedia.org/wiki/Innogy_(Schiff). [Zugriff am 2020].

[140] TU-Berlin, „ELEKTRA 1," 30 09 2019. [Online]. Available: https://www.marsys.tu-berlin.de/menue/forschung/elektra/.

[141] K. F. Juelsgaard, „HySEASIII - Zero Emission H2 Ferry to Shapinsey, Orkney," Florø, 2018 .

[142] HySeasIII, 2020. [Online]. Available: https://www.hyseas3.eu/. [Zugriff am 2020].

[143] A. Hotchkiss, „Ferguson Marine to develop world-first renewables-powered hydrogen ferry," 2020. [Online]. Available: https://www.scottish-enterprise-mediacentre.com/news/ferguson-marine-to-develop-world-first-renewables-powered-hydrogen-ferry. [Zugriff am 2020].

[144] J. C. G. Trillos, D. Wilken und T. V. Urte Brand, „HySeas III: The World's First Sea-Going Hydrogen-Powered Ferry –A Look at its Technical Aspects, Market Perspectives and Environmental Impacts," DLR –Institut für Vernetzte Energiesysteme, Carl-von-Ossietzky-Straße 15, 26129 Oldenburg, Oldenburg, 2019.

[145] Bahnfrend, Artist, *The Scandlines ferry Berlin passing through Warnemünde on arrival at Rostock, Germany, from Gedser, Denmark.* [Art]. Wikimedia Commons, 2019.

[146] Scandlines Hybrid, „Scandlines' Hybridsystem," 2018. [Online]. Available: https://www.scandlines.de/uber-scandlines/greenagenda/vores-hybridsystem. [Zugriff am 2020].

[147] Scandlines Berlin, „Hybridfähre „Berlin"," 2018. [Online]. Available: https://www.scandlines.de/uber-scandlines/uber-scandlines-titelseite/fahren-und-hafen/berlin. [Zugriff am 2020].

[148] Binnenschifffahrt , „Erstes Binnenschiff fährt komplett auf Bio-Kraftstoff," Binnenschifffahrt Magazin für Technik und Logistik, 2019. [Online]. Available: https://binnenschifffahrt-online.de/2019/04/featured/6757/binnenschiiff-faehrt-komplett-auf-bio-kraftstoff/. [Zugriff am 2020].

[149] Rotterdam Port , „Biokraftstoff für jedes Schiff im Rotterdamer Hafen," Port of Rotterdam N.V., 2015. [Online]. Available: https://www.portofrotterdam.com/de/nachrichten-und-

pressemitteilungen/biokraftstoff-f%C3%BCr-jedes-schiff-im-rotterdamer-hafen. [Zugriff am 2020].

[150] T. Bruns, „Hurtigruten: Erste Testfahrten mit Biodiesel,“ Schiffsjournal, 2019. [Online]. Available: https://www.schiffsjournal.de/hurtigruten-erste-testfahrten-mit-biodiesel/. [Zugriff am 2020].

[151] Wikipedia Amundsen, „Roald Amundsen (Schiff),“ 2019. [Online]. Available: https://de.wikipedia.org/wiki/Roald_Amundsen_(Schiff,_2019). [Zugriff am 2020].

[152] Hurtigruten Amundsen , „MS Roald Amundsen,“ 2019 . [Online]. Available: https://www.hurtigruten.de/schiffe/ms-roald-amundsen/#. [Zugriff am 2020].

[153] FhG, „Biosprit für den Schiffstank - Fraunhofer-Info (4.5.2020),“ Fraunhofer Gesellschaft, 2020.

[154] INWL, „Potenzialanalyse Methanol als emissionsneutraler Energieträger für Schifffahrt und Energiewirtschaft,“ INWL Institut für nachhaltige Wirtschaft und Logistik inwl gemeinnützige GmbH, Rostock, 2018.

[155] Wikipedia CVN78, „Gerald R. Ford-class aircraft carrier,“ 2017. [Online]. Available: https://en.wikipedia.org/wiki/Gerald_R._Ford-class_aircraft_carrier. [Zugriff am 2020].

[156] M. Ragheb, „NUCLEAR MARINE PROPULSION,“ 2019.

[157] Wikipedia Sevmorput , „Sevmorput (Schiff),“ 2020. [Online]. Available: https://de.wikipedia.org/wiki/Sevmorput_(Schiff). [Zugriff am 2020].

[158] Wikipedia 50 Let, „50 Let Pobedy (Schiff),“ 2013. [Online]. Available: https://de.wikipedia.org/wiki/50_Let_Pobedy_(Schiff). [Zugriff am 2020].

[159] P. Reisen, Artist, *Atomeisbrecher "50 Let Pobedy".* [Art]. Polar Reisen, 2020.

[160] R. Spekking, Artist, *Landstromversorgung Schiffs-TankE im Rheinauhafen Köln-9787.jpg.* [Art]. Raimond Spekking / CC BY-SA 4.0 (via Wikimedia Commons).

[161] A. John, Artist, *Ladeinfrastruktur der "Ampere" bei Lavik (Norwegen).* [Art]. 2018.

[162] PTB, „Dokument: 20/0104,“ 2015. [Online]. Available: http://www.ptb.de.

[163] PTB, „Countdown zum neuen SI,“ 2020. [Online]. Available: www.ptb.de/cms/forschung-entwicklung/forschung-zum-neuen-si/countdown-zum-neuen-si.html.

[164] V. K. Cheng und G. P.Hammonda, „Life-cycle energy densities and land-take requirements of various power generators: A UK perspective,“ *Journal of the Energy Institute,* pp. 201-213, 2017.

[165] L. Gagnon, C. Belanger und Y. Uchiyama, „Life-cycle assessment of electricity generation options: the status of research in year 2001,“ *Energy Policy, 30 (14),* pp. 1267-1278, 2002.

[166] Gagnon, L., „Electricity Generation Options: Energy Payback Ratio – Factsheet,“ Hydro Quebec, Quebec, Canada (2005), Quebec, Canada, 2005.

[167] El-Fadel et al., „Choosing Green Energy: A Consumer's Guide to Sustainable Electricity,“ US Environmental Working Group [EWG], Washington DC, USA, 2000.

[168] ADAC, „Mobilität in Deutschland - Ausgewählte Ergebnisse,“ Allgemeiner Deutscher Automobil-Club e.V., Ressort Verkehr, München, 2010.

[169] Andreas Ahlswede, „Anzahl der Elektroautos in Deutschland von 2006 bis 2020,“ 11 03 2020 . [Online]. Available: https://de.statista.com/statistik/daten/studie/265995/umfrage/anzahl-der-elektroautos-in-deutschland/. [Zugriff am 2020].

[170] e.on, „Der Stromverbrauch bei Elektroautos : Wieviel verbraucht ein E-Auto auf 100 km?,“ 2019. [Online]. Available: https://www.eon.de/frag-eon/themen/e-mobility/fragen-und-antworten/der-stromverbrauch-bei-elektroautos-wieviel-verbraucht-ein-e-auto-auf-100-km/. [Zugriff am 2020].

[171] Wikipedia Energieverbrauch, „Energieverbrauch,“ 01 05 2020. [Online]. Available: https://de.wikipedia.org/wiki/Energieverbrauch. [Zugriff am 2020].

[172] A. Breitkopf, „Stromverbrauch in Deutschland von 1991 bis 2019,“ 18 03 2020. [Online]. Available: https://de.statista.com/statistik/daten/studie/164149/umfrage/netto-stromverbrauch-in-deutschland-seit-1999/. [Zugriff am 2020].

[173] P. Kohli, Artist, *Cold Ironing Schematic.* [Art]. Eigenes Werk, 2009.

[174] IVH, „Landstromversorgung von Kreuzfahrtschiffen,“ IVH-INDUSTRIEVERBAND HAMBURG, Vattenfall Europe Distribution Hamburg GmbH; Germanischer Lloyd AG; Siemens AG, Hamburg, 2010.

[175] Scandlines, „Fahrplan Puttgarden-Rødby,“ 2020. [Online]. Available: https://www.scandlines.de/tickets-und-tarife/tickets-und-preise/puttgarden-rodby.

[176] Scandlines-M, Interviewee, *Telefonat zum Projekt BSRelectric, zum Weissbuch und angrenzenden Themen..* [Interview]. 07 2020.

[177] A.John, Artist, *Umläufe und Ladeaktivitäten der Fähre in Rødby und Putgarden.* [Art]. Eigenes Werk, 2020.

[178] PREISVERGLEICH, „120-Städte-Studie Stromverbrauch: Das sind Deutschlands Stromverschwender-Städte,“ 2020. [Online]. Available: https://presse.preisvergleich.de/120-staedte-studie-stromverbrauch-das-sind-deutschlands-stromverschwender-staedte-2/. [Zugriff am 2020].

[179] ADAC Laden, „Wallbox: Elektroauto-Ladestation für zu Hause - Die wichtigsten Tipps,“ 2020. [Online]. Available: https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/laden/elektroauto-laden-wallbox-faq/. [Zugriff am 2020].

[180] T. Sutharssan, D. Montalvão, Y. Chen, W.-C. Wang, C. Pisac und H. Elemara, „A review on prognostics and health monitoring of proton exchange membrane fuel cell (Schematics-of-a-fuel-cell-stack-operation-and-components),“ *Renewable and Sustainable Energy Reviews,* Nr. 10.1016/j.rser.2016.11.009, 2016.

[181] J. Milewski und J. Lewandowski, „Analysis of Design and Construction of Solid Oxide Fuel Cell in Terms of their Dynamic Operation," *Archivum Combustionis Vol,* Nr. 30, 2010.

[182] M. Klingele, M. Breitwieser, R. Zengerle und S. Thiele, „Direct deposition of proton exchange membranes enabling high performance hydrogen fuel cells," Royal Societey of Chemistry, 2015.

[183] YuanBo, „Membrane Electrode Assembly Has Stable Structure and Working Performance," YuanBo Engineering Co. Ltd. Polymer Material, Industrial Zone, China., 2020. [Online]. [Zugriff am 01 06 2020].

[184] Fuelcellstore, „Fuel Cell MEA," 2020. [Online]. Available: https://www.fuelcellstore.com/direct-methanol-mea. [Zugriff am - 06 2020].

[185] Alibaba (FC), „PEM Fuel Cell Stack," 2020. [Online]. Available: https://www.alibaba.com/product-detail/PEM-Fuel-Cell-Stack_142720354.html. [Zugriff am 01 06 2020].

[186] HydroGeit, „Wissen / Brennstoffzelle: Kosten," 1999. [Online]. Available: Wissen / Brennstoffzelle. [Zugriff am 2020].

[187] J. Paeger, „Eine kleine Geschichte," 2006 – 2019. [Online]. Available: http://www.oekosystem-erde.de/html/geschichte_erdoel.html.

[188] A. John, Artist, *Klassifizierung von Fähren.* [Art]. Nach Recherchen, 2020.

[189] Ampereship, Artist, *Abbildung, computergeneriert, für die neue Fähre für Rostock..* [Art]. Ampereship GmbH, 2020.

[190] Google, Artist, *Merriweather Font.* [Art]. Google Fonts, 2020.

[191] NHA, 2020. [Online]. Available: http://www.hydrogenassociation.org.

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