Framework project AquaFLEAW

INTERREG V A Deutschland - Nederland

1. The “Green Deal” - incentive for new mobility approaches in shipping?

With the concept of a "Green Deal"[1)] presented by the EU Commission on December 11, 2019, Europe would like to be the world's first continent to be climate-neutral by 2050 and, on the way, to reduce greenhouse gas emissions to at least 55% of the 1990 levels by 2030. This requires challenging approaches in many areas of public life and infrastructure, which of course also have to meet with acceptance within the EU population in order to develop a corresponding effect. Measures planned to date include the areas of energy supply, transport, trade, industry, and agriculture and forestry, with electricity becoming the backbone of the entire energy system. By focusing on the direct use of “green” electricity, the needs for electrical energy will more than double by the year 2050. In addition to the expansion of renewable energy sources such as wind, solar and hydroelectric power plants, the use of supplementary and sustainable energy sources, such as green hydrogen, is necessary to cover the energy demand. This is all the more true because, due to Germany's geographic situation, a significant expansion of hydropower would be difficult. On the other hand, offshore wind farms, which are celebrating their 30th anniversary this year (2021), are an important component in the energy mix. However, there are stumbling blocks here too, for example the expansion of offshore wind turbines has declined significantly since 2020. In addition, new studies[2)] show that the expansion of offshore wind farms cannot be increased indefinitely, without accepting significant yield losses. A study by the Helmholtz Center Hereon in the journal Nature Scientific Reports[3)] shows that these losses in efficiency can be considerable. Wind farms are usually built in groups, so-called wind farm clusters. If wind flows through a large offshore park, the air flow slow down, this means that neighboring wind parks sometimes slow each other down. The braking effect reaches an average of 35 to 40 kilometers - in certain weather conditions even up to 100 kilometers - with a loss of performance of 20 to 25%.

Since there are limits to renewable energy sources in terms of weather conditions and land consumption, an integrative, sometimes flexible, decentralized approach is required that takes all sectors into account. In addition to the actual energy generation, innovative solutions for energy storage are also required. In Germany alone, around 6 terawatt hours from renewable energies were down regulated in 2020 and therefore not used, because the power could not be consumed by the electricity grid. Regardless of the degree of efficiency, the generation of green hydrogen by electrolysis directly at the source, is ideal here. The spectrum for the use of hydrogen ranges from energy storage to synthetic fuel to energy suppliers for fuel cells. In order to do justice to the complexity of the topic, a separate chapter is devoted to this topic in the study.

One sector that receives special attention in the “Green Deal” can be summarized under the slogan “zero-emission mobility”. This not only includes heavy goods vehicle traffic, but also includes personal mobility with efficient, safe and environmentally friendly means of transport. Transport

now accounts for around 25% of total greenhouse gas emissions in the EU. This proportion has increased again, especially in recent years. In order to achieve the stated goal of climate neutrality by the year 2050, it is necessary to reduce greenhouse gas emissions caused by traffic by 90%. Or to put it simply - **no successful energy transition without a traffic transition**. In the absence of other alternatives, the transport turnaround must first concentrate on the electrification of drives. In order for this to be possible across all applications and segments, a sensible combination of batteries and fuel cells is required, which ideally can be usefully supplemented.

While considerable technological advances have been made in road, rail and air transport, shipping and waterborne traffic seem to be somewhat neglected. In its “Factsheet” [4)] on sustainable mobility, the EU Commission has set a 25% increase in the volume of transport via inland waterways by 2030 as a goal. Especially the Niederrhein region, together with the cross-border support area EUREGIO Deutschland-Nederland, has a role model function due to the large number of existing waterways and the location of the largest inland port in the world in Duisburg[5)].

It is therefore an important goal of this study to present novel, innovative and at the same time climate-neutral concepts for means of transport on the water. The focus is on the existing niche of personal mobility, with smaller ships for up to six people. It describes vehicles that are equipped with a new type of self-regulating 3D vector hydrofoil system technology and an electric drive. Equipped with variable energy systems, these can be used flexibly in different applications. However, such a concept also allows inland shipping to be scaled to smaller, autonomously driving electrified boats, accompanied by a high degree of flexibility in loading capacity and high potential for cost savings, while at the same time being climate neutral. In addition, there are hardly any obstacles for this type of watercraft, on poorly accessible waterways or trips at low water levels.

Ultimately, it is important to activate the already existing potential of the Niederrhein region for the development of innovative mobility solutions on the water, but also to sensitize individuals to the opportunities that arise through the use of our waterways.

2. History, State of the Art and Vision

Nowadays mobility is more and more constrained to the amount of energy available since the transition to renewable energy is becoming more evident. This energy constraint has been around for sailing crafts ever since the first boats emerged (either powered by man or wind). One of the obvious goals to transport goods over a larger distance is to reduce the parasitic drag. One way to reduce the drag of a boat is to reduce the contact surface. Besides energy efficiency, hydrofoils add stability and ride comfort by hoovering over impinging waves. This makes hydrofoiling crafts more suitable for the transportation of people than other designs.

Fig. 1) Hydrofoiling has been around since the late eighteen hundreds (historic image with ladder foil configuration).

Ever since, different boats have been fitted with hydrofoils, such as ferries, military boats and sailing craft. To distinguish between different hydrofoil techniques, one must know basic physics of flying. In the simplest form, lift of a body can be described as:

$$Lift = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot Cl$$

Where ρ (gr.: rho) is the density of the medium in which the body is submerged. Water is much denser then air and thus delivers more lifting force. The same holds for the drag which has a similar physical relation. The speed v is squared in the lift relation. The amount of lifting force is increasing quadratic for increasing speed. Therefore, for a foil to operate in a wide range of speeds, one of the other parameters has to be changed to end up with equilibrium.

This can only be done by changing either the surface area *A* or the lifting coefficient *Cl*. Changing the surface area of the lifting body is the most straightforward way. It can be regulated by “surface piercing” foils, where the tips of the foil pierce the surface and effectively remove surface area form the water (Fig. 2).

Fig. 2) Surface piercing foils – E-Foiler & Flo1 Aeronamics.

If the surface area is kept constant, by means of “fully submerged foils”, changing the lifting coefficient of a foil can be done by changing the angle of the incident flow. A change of the angle can be made by a mechanical coupling to the water plane, but also electro-mechanical (fly-by-wire). The latter is something that has been exploited the last decades, since computational power has become more efficient and easily available.

Fig. 3) Submersed foils configuration – with active lift control (mechanical) HAN-Solar boat PwrdbyQ.

By nature, long and slender foils are more efficient than shorter models for their given area. The aspect ratio [span/chord] is therefore a crucial efficiency contributor. This however goes into the practical and engineering constraints of materials. Also for boats, who traditionally land in a harbor it is very inconvenient to have appendices larger than the beam of the hull. Curved hydrofoils are ingenious feats of engineering in the terms of buckling and bend. Predicted and controlled bend of the hydrofoils under loads are always taken in account, when designed the hydrofoil’s geometry.

As stated before, two different control strategies are available, either by having “surface piercing” or “fully submerged” hydrofoils. The first one offers benefits in terms of robustness and simplicity, but requires extensive structural engineering. The latter is generally more energy efficient, especially if fly-by-wire is adapted as the control strategy (Fig. 3). For sailing vessels, foil designs do not only reduce the drag, but also increase the amount of power. This is because the stability is often greatly increased by increasing the righting arm. With a jump in boat speed, more energy from the wind can

be created by the increase in apparent wind speed over the sails.

Developments of the last decades make the design and production of hydrofoils more feasible. Highly efficient designs consist of thin highly loaded structures, which are made up of double curved surfaces. Variable profiles and (induced) twist are standard features. These designs are benefiting from progress in computational fluid dynamics (CFD) - which push the overall efficiency, computer aided design (CAD) - which enables designers to come up with ever more sophisticated designs, as well as from fiber reinforced plastics (FRP's) - from which the production processes especially suit double curved parts and the structures manufactured have a high stiffness to weight ratio.

A drawback of adding foils is that more complexity is added to the vessel and loads on structures are not to be underestimated. A large part of the hydrofoil development projects have been un-welcomely surprised by structural failures in the platform and structures created by the lift induced loads. Hydrofoiling craft required a higher initial investment to develop and build, compared to non-foiling boats. With sufficient reduction of energy used, the total cost of operation could however be reduced significantly. In the last decade hydrofoil developments have been sped up in rapid pace changing boat design and creating a revolution in boat behavior.

The state of the technology - Zooming in on submersed foils with active lift controls:

1. <u>Fly by wire</u> – is being introduced to newly developed boats, with CANBUS systems connecting all sensors and control systems together.
2. <u>Highly engineered foils</u> with extensive CFD analyses and integrated structural engineering to manipulate deforming under load.
3. <u>Active ride height control</u> with height and acceleration sensors - eliminating draggy and heavy mechanical sensing equipment.

Vision – what for effect has foiling in the near future?

1. <u>Reduction of parasitic drag</u> – less energy consumption brings you further and moves you faster with the same amount of energy used.
2. <u>Increase platform stability</u> – better seakeeping by reducing ship motion in waves and create a safer and more comfortable ride. Less injuries and better performance of seaman at sea due to less seasickness related issues.
3. <u>High Speed potential</u> – hybrid craft whereas "Archimedes" modes have drastic drag increase with speed. Hybrid craft that can dock like a traditional "Archimedes" craft and can operates without foils as well in e.g. situations, where speed limits apply or the lack of fuel/energy don't make foiling possible.

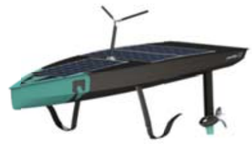
3. Idea of the AquaFLEAW - Application Areas

In Europe but also from a global perspective, many countries offer a wide variety of inland waters, canals and waterways, which constitute the target audience for the proposed concept. The combination of high ecological sensitivity, high density of urbanisation and the rising awareness to build a sustainable future, however, asks for novel concepts of transportation. The key idea of this project is to develop a watercraft that addresses the current vacuum of innovation regarding the linking of the game-changing hydrofoil technology and the need to provide smart and efficient solutions for transportation. The main requirements can be listed as follows:

- Use of the watercraft for leisure purposes, as a passenger carrier/ taxi or for the transport of goods on the last step of the supply chain (last 1-10 km)
- The barrier to obtaining an operating permit and licence is to be kept on a minimum level
- Vehicle length is restricted to 3 - 6 m to maintain a general design concept
- Max. Passenger capacity of 4 or an equivalent payload of max. 300 kg (max. total ≈ 500 kg)
- Fully electric drive technology
- Propulsion sub-surface or aerial (dependent on operational area)
- Operating duration up to 1.5 h (function of speed and payload/ passengers)
- Preferred operation in hydrofoil-mode (function of foil configuration, driving speed, payload)
- Easy to operate for the inexperienced user
- Intelligent adaption of drive mode and foil adjustment, concerning the specific operation conditions (passengers, payload, speed)
- Lightweight and based on sustainable materials easy to recycle (provident consideration of ecologic cycle)

From an ecological perspective, the electric drive technology shows the potential to significantly reduce the CO_2 in a consolidated balance, while, during operation, no CO_2 or alveolar dust is emitted at all. In combination with the reduced acoustic signature due to the absence of low-frequency noise of a combustion engine and the low-penetrating drive technology when in Hydrofoil-mode, the watercraft also facilitates an operation in ecologically sensitive areas. That way, a small and eco-friendly watercraft is developed, which cause neither bow nor stern waves, when in foil-mode, and contributes to a reconcilability of technology, urbanisation and environment.

The novel concept aims at designing a watercraft, which is equipped with a 3D-Vector-hydrofoil technology, enabling an adaptive configuration as a function of specific customer needs[6)]. The current state of technology offers no electric-driven watercraft of the announced dimensions and



purpose. Moreover, all hydrofoil systems available are inflexibly linked to certain initial design conditions, giving no freedom to react to changing operating conditions. On the other hand, increasing the degrees of freedom by implementing intelligent actuators and sensors allows direct and low-threshold reactions to the operation mode and a high level of automatization and user-friendly operation of the watercraft at highest efficiency standards.

4. Drive Technology and Drive Concepts -
Optimization of the boat body in regards of flow resistance

To achieve optimum performance while guaranteeing a high degree of freedom during the design process, multiple influencing parameters need to be consolidated and optimised. Table 1 provides the first overview of potential influencing parameters (independent) and the resulting target quantities (dependent), which can be used to describe the performance of the watercraft at a sufficient degree.

Influencing Parameters	**Unit**		**Target Quantities**	**Unit**
Payload	kg		Coefficient of drag	--
Speed	m/s		Coefficient of lift	--
Vessel length	*m*		*Skin Friction Coefficient*	--
Foil configuration	multiple		Power consumption	kW
total weight	kg		Operation Duration	hrs

Tab. 1) Contrasting parameters of influencing vs. target values.

For the intended design and definition of the hydrofoil watercraft, numerical state-of-the-art simulations using Computational Fluid Dynamics (CFD) are used to predict the hydrodynamic performance as a function of the operating conditions. As outlined in Fig. 4, the defined influencing parameters are handed over to a parametrized 3D CAD design of a general blueprint model.

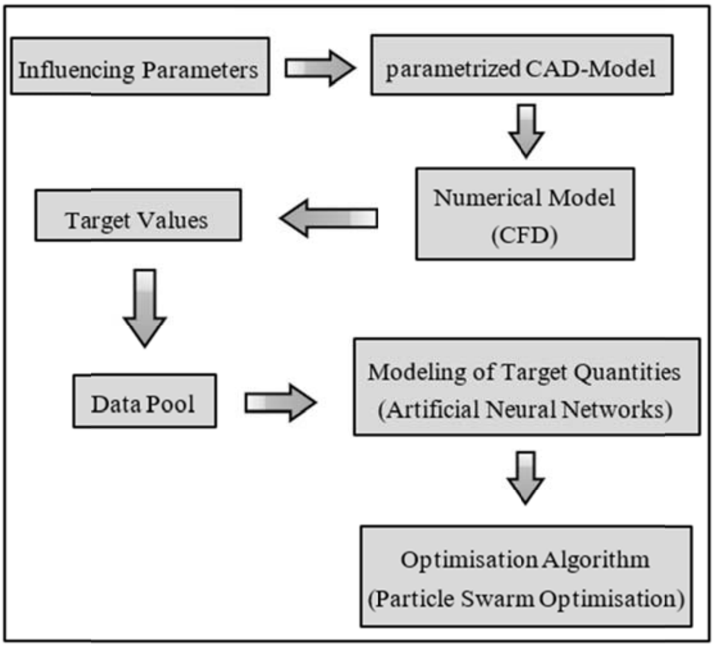


Fig. 4) Metamodel concept of interrelating influencing parameters and target values by use of numerical simulation and optimization

Based on this model, the shell structure is extracted and prepared for the numerical simulation. This simulation is performed using the commercial *ANSYS CFX Workbench* by conducting two-phase air/water simulations at varying flow speeds or Reynolds numbers, respectively. The extracted target values are the flow resistance as well as the lift and drag forces. Deriving the power consumption as well as verifying the possible payloads allows characterising the watercraft on a fundamental level as a function of the specific input parameters.

Repeating the numerical simulations for multiple sets of input parameter-combinations, preferably based on a Latin-Hypercube sampling approach, provides a data pool, which allows preceding the obtained results towards optimum solutions. First, low-layer artificial neural networks are used to model the watercraft's specific performance as a function of the influencing parameters (Fig. 5). If necessary, the prediction accuracy of the model can be further improved by evaluating the statistical uncertainties of the model and deriving additional test cases, which can be incorporated into the model. As soon as the metamodel is generated with the desired accuracy, no further computationally expensive simulations of the model via CFD need to be performed. Instead, the ANN-based metamodel with a data volume of a few kilobytes is used to predict the performance of the watercraft as a function of the influencing parameters.

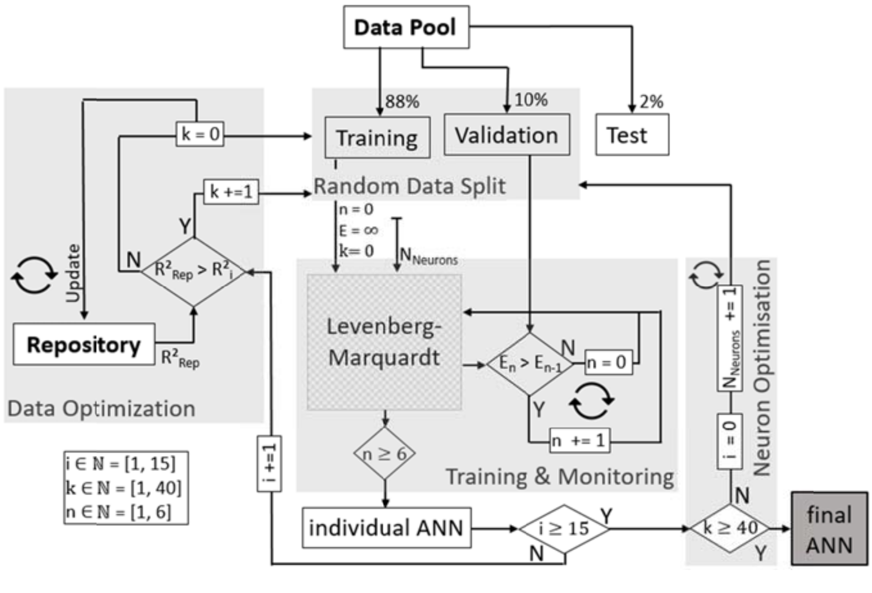


Fig. 5) Flow chart of periphery for training artificial neural networks[7)]

However, analysing individual target values independently often does not suffice to describe a system to the desired level of granularity, since multi-objective optima are needed, especially when two or more objectives are conflicting. This is particularly true for complex systems such as the intended watercraft. This means that the optimum solution for one objective can lead to an undesired solution for another objective.

Computational expensive unbiased multi-objective optimization can compute Pareto optimal solutions, visualized by so-called Pareto fronts (Fig. 6), which separate non-efficient from non-realisable solutions. The Pareto fronts also help to indicate the best solutions and are computed via the multi-objective particle swarm optimization (MOPSO) algorithm as proposed by Coello et al.[8]. This chosen algorithm is used to optimize multiple continuous cost functions to obtain a combined optimum. This makes a premature weighting of the individual target values superfluous and allows choosing the optimum set of influencing parameters / design parameters based on the specific operating conditions. Be it during the engineering loop or even during operating the watercraft; the suggested multi-objective optimisation approach allows tailoring the design parameters of the watercraft specifically to the actual operating conditions. This is expected to provide a maximum in efficiency and performance.

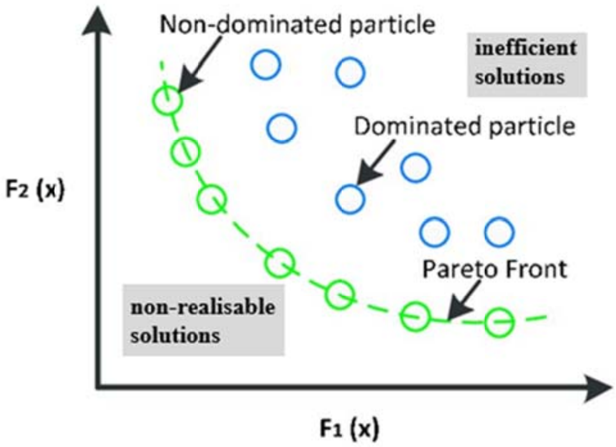


Fig. 6) Dominated, non-dominated and Pareto-front solution set, adopted from Kumar et al. [9]

5. Electric drive design and optimization

Current research and development projects in the field of e-mobility are mainly focused nowadays on the energy supply chain, by covering related problems like electricity generation and –storage under zero-emission conditions. Next to this main area of interest, an important factor for further optimization and development steps seems to be missing the public attention. All existing e-mobility solutions require at least one electric drive to convert electrical into mechanical kinetic energy. In this context, an electric drive is almost exclusively an electric motor, which also has to be optimized for the area of application. There are already specially designed electric motors for air and especially land vehicles, but these are missing for use on water. For reasons of efficiency and energy saving, it does not make sense to use standard motors that have been developed for other areas of application. One goal for successful watercraft in the future must be to use specially designed electric motors that are adapted to the aqueous medium. Therefore, in a first step, it is necessary to describe the typical parameters that define the power and efficiency of an electric motor.

Selecting the right e-motor to drive an application is rarely easy because the properties of the technologies have different consequences for product design. Factors such as speed, torque, available space, noise emissions, weight, costs and precision have to be brought under one roof. There are also several technologies to choose from: brushless DC motors, coreless DC motors and stepper motors. So let's go through the application parameters one by one and see how they influence the choice of motor technology.

- Engine speed (rpm)
  One of the first factors to consider when designing a watercraft is the required output speed of the drive. Due to their design and electronic commutation, brushless DC motors are best suited for operation at higher speeds. With brushed DC motors, the brush wear increases with the speed, which shortens the service life. Stepper motors have a higher number of pole pairs and are therefore not designed for high speeds, despite electronic commutation.

- Torque (Nm)
  The next factor is the torque that the drive must deliver, whereby both the continuous torque and any time-limited peak torques play a role. The individual motor technologies are characterized by different maximum torques in continuous operation. Depending on the application, all three technologies are able to deliver the necessary torque. It is also conceivable to connect a gear to increase the torque of the drive. It should be noted, however, that the speed and efficiency decrease accordingly. Therefore a gear is not the first choice in an AquaFLEAW application.

- Lifespan time
  The task of the drive is usually measured in a number of cycles of a certain length per day or in operating hours per day with a certain frequency. This can be used to determine the approximate number of hours that the drive will run during the expected product life. This has an impact on the choice of motor. Brushed DC motors have a mechanical commutation system that wears out over time and limits the life of the motor. Brushless DC motors and stepper motors are electronically commutated and are therefore not subject to brush wear. This gives them a longer life expectancy.

- **Mounting space**
  Before making any further considerations, it is important to ensure that the desired motor technology is available with dimensions (diameter and length) and weight that can accommodate the space provided for the drive. While the speed and torque specifications can usually be met by at least one of the motor technologies or several sub-variants, the less space is available, the higher the required power density.

- **Operational phases**
  Typically, the engine does not run continuously under full load. Rather, operating phases alternate with rest periods. The temperature rise of the engine depends on what this cycle mode looks like. All motors are designed for a certain maximum nominal temperature. If this is exceeded during operation, the components inside the motor can be damaged. The rise in temperature depends on the current consumption: the higher the current, the faster the temperature rises. Since the current is proportional to the torque output, it makes sense to increase the motor torque with a higher motor current while keeping the motor as small as possible. However, the requirements must be checked very carefully so that the current consumption does not lead to the motor overheating.

- **Energy supply**
  For this application, the motor is supplied with energy via batteries or accumulators, so that the current consumption of the motor is an important criterion. The lower the power consumption (while guaranteeing the necessary performance), the longer the battery will last between charging processes. The smallest possible size and weight also become a priority.

Due to all the facts described above, a brushless DC (BLDC) motor with variable speed control appears to be best suited for the AquaFLEAW concept. For a small, light boat, a directly driven BLDC motor without a gearbox also seems to be ideal.

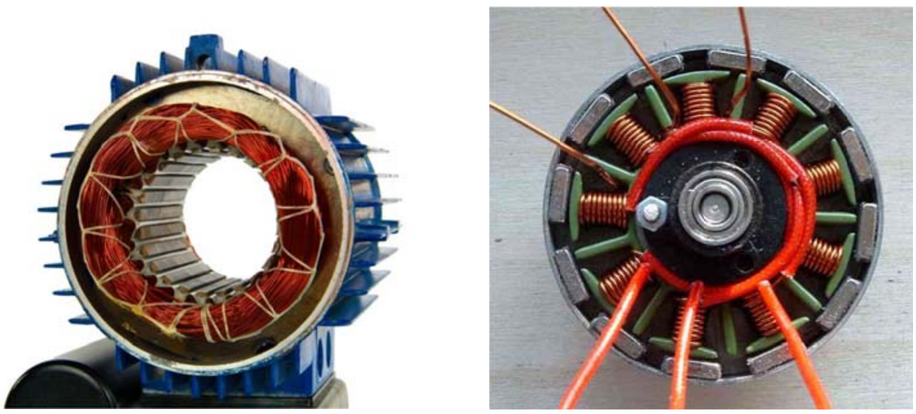


Fig. 7) Detailed view of a standard BLDC motor, with coiled stator windings and neodym-magnets on the bell [10].

As can be seen from Fig. 7, the production of the core components of a BLDC motor requires not only special materials, but also high precision and technical effort. In particular, the stacking of individual stator sheets with embedded insulation layers, as well as the correct winding of the stator coils and their alignment with the corresponding magnetic fields within the bell, have a significant influence on the efficiency and performance.

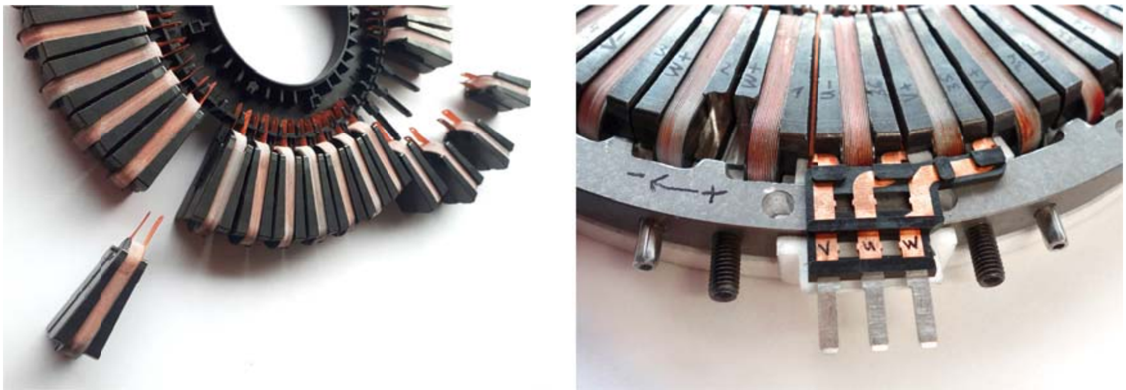


Fig. 8) Additive Drive Technology: 3D-printed copper coils replace normal stator wirings[11)]

On the other hand, new additive manufacturing technologies are available that can bring electric motor design a big step forward. In combination with innovative materials, this could represent a game changer for the future development and optimization of electric motors. One example of such an innovative development is the *Additive Drive Technology* [11)], which uses 3D-printed copper coils for the stator (Fig. 8). The higher copper content in the electric motor reduces losses and improves the thermal coupling of the winding. A 45% performance increase was registered when these type of copper coils were used in a BLDC motor. The 3D-printing of individual coils offers the greatest possible flexibility. Therefore, individual coils can be designed for all conceivable motor geometries, which lead to less installation space, better thermals and higher efficiency.

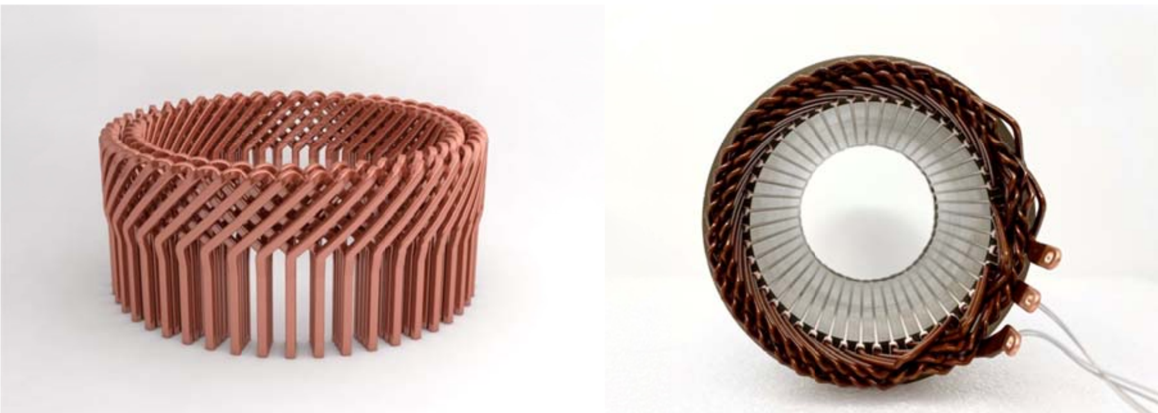


Fig. 9) Novel hairpin concept: 3D-printed hairpin windings replace wound copper wires[7)]

Especially for high-performance applications such as AquaFLEAW, innovative 3D-printed hairpin windings (Fig. 9) offer up to 30% more torque in the same installation space. The process can also be automated more easily than conventionally wound motors and is significantly more cost-effective

due to the shorter production times.

Fig. 10) Optimized Cobalt-Iron Alloys have the Highest Saturation Polarization [12)]

In terms of material development, new types of soft magnetic materials allow the magnetic flux to be optimized in high performance motors too. In contrast to conventional soft iron metals, 49% cobalt-iron alloys offer an unmatched high magnetic saturation of up to 2.3 T. They are therefore generally suitable for all applications, where high flux density and minimal weight are required. A further addition of 2% vanadium offers low coercive field strengths and results in superior performance parameters for electric motors and generators (Fig. 10). By combining all these innovative developments into one product, electric motors should in future be available, whose energy efficiency and performance potential is specially designed for watercrafts.

But not only electric motor components can be manufactured with special 3D-Printing technologies. Those technics can also be used to manufacture other smaller parts, for example of the boat hull. Even the choice of standard Fused Deposition Modeling (FDM) 3D-Printing, for rapid prototyping and parts production in the AquaFLEAW concept lowers costs and enables better "time-to-market" products. Various applications of the FDM 3D printing technology are of important added value in the development and production launch of the Hydro Foil boat, why three applications are presented below:

- For presentation purposes, a true-to-scale model made of PLA (Polylactid Acid), with a maximum size of 500 x 400 x 700 mm (LxWxH) can be printed on a standard Opiliones 2L 3D-printer.
- During engineering phase first prototyping parts can be printed swiftly with the same FDM technique and raw material (PLA) to visualize any designed parts at very low cost.
- During the development the material used can also be changed within the FDM technology, in order to achieve some of the required component specifications.

Basically, there are three different and inexpensive material types to choose from in order to meet the required functionality.

- PETG (Polyethylene Terephthalate Glycol - modified)
- High-Performance PA (Polyamide)/Carbon Fiber Composites
- FDM 3D-printable metals, such as Stainless steel 316 (using “very low cost” *MakeItMetal* direct granulate)

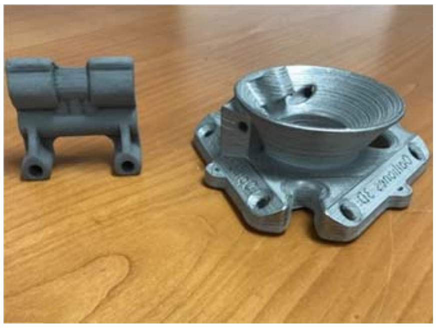


Fig. 11) *PETG material* *PA/Carbon Fiber Composites* *Metal FDM granulate*

6. Economic potential

A recreational hydrofoil designed to make traffic cleaner and smarter by helping to become carbon neutral. AquaFLEAW is a fully solar / electric 4-person hydrofoil recreational watercraft designed for use on inland waterways, canals and waterways. AquaFLEAW combines groundbreaking hydrofoil technology and the need to provide intelligent and efficient transportation solutions. Compared to conventional boats, the AquaFLEAW watercraft is more stable in inclination and "ride height" due to the highly innovative geometry of its hydrofoil arms. It has less torso resistance, no torso friction, which leads to an energy saving of more than 50%. The jet boat is quiet, comfortable and fast with a cruising speed between 25 - 45 km/h.

<u>Feasibility - Timeline to Valorization</u>

- During a two to three year follow up project, AquaFLEAW can be developed to a full-scale demonstrator.
- The second year of the project will be used to present the AquaFLEAW watercraft to an investor and a leading supplier of “Leisure sloops” on the European market.
- This supplier will act as a Production- and Roll Out partner for AquaFLEAW to reach the market for Leisure Watercrafts.

Project finance of the Follow up Project for the first two years are about 850.000 EUR (partly own financing, partly external). During that timeframe the AquaFLEAW consortium operates from the premises of a project partner in the Netherlands. After the project ends, the production of AquaFLEAW watercrafts will be transferred to the premises of the production/Roll out Partner.

In Holland the yearly sales[13)] of leisure watercrafts like motorized sloops and motorized fishing boats for inland waters, accumulates to 1200 new boats sold in 2016. A Target of 60 AquaFLEAW sold per year at a price of ~40.000 EUR each is ambitious, but realistic.

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