WETFEET

D 7.2 – Supply chain (RML) study of the innovative components for large scale deployment

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5	

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EXECUTIVE SUMMARY – WAVEC

This report presents Deliverable 7.2, of the WETFEET H2020 project – report with the analysis of the Manufacturing Readiness Level (MRL) for the large-scale deployment of the innovative components.

Objective

The objective of this task is to carry out a preliminary review of suitable manufacturers to supply the innovative components introduced by the breakthroughs, which includes the dielectric generators, the structural membrane, the tetra-radial air turbine and the water turbine as power-take-off.

The aim of the WETFEET project is to raise the breakthrough technologies TRL from concepts and its applications (TRL 2), by proving its operability and validity by testing them individually in the laboratory (TRL 3) and applied to small scale WEC prototypes in a wave tank (TRL 4). Following this stablished objective, the MRL expected for the breakthroughs is MRL 3 - 4.

Overall Results

The results of the MRL assessment show that the WETFEET breakthroughs have been studied wide and deep enough to achieve overall satisfying results regarding the MRL objective.

The Manufacturing Readiness for the Tetra-radial turbine is the most advanced of the manufacturing capabilities assessed, with no result under MRL 4.

The Water turbine was the breakthrough assessed with the lower manufacturing capabilities overall, reaching MRL 3 in two risk areas, alongside with the Power, Sensing and Controlling system of the Dielectric Elastomeric Generator, which reached MRL 3 in 3 risk areas.

Follow-on Work

In order for the breakthroughs to have a higher and more complete MRL, the other risk areas not considered in this assessment should also be studied and assessed in order to lower the risk associated with the manufacturing processes. These risk areas include *Quality Management, Manufacturing Workforce (Engineering & Production)* and *Manufacturing Management.*

Regarding the timing of the MRL assessment, it should be revised later in the project, when the study of all technical and economic matters has been performed, in order to have the complete information about the technologies and components.

1. Introduction

Technology developers face problems in manufacturing systems—they cost far more and take much longer to build than estimated, says the United States Government Accountability Office [1]. Significant cost growth occurs as programs transition from development to production, and unit-cost increases are common after production begins. Contributing factors to these problems include: inattention to manufacturing during planning and design, poor supplier management, and a deficit in manufacturing knowledge among the acquisition workforce. Essentially, programs did not identify and resolve manufacturing risks early in development, but carried risks into production where they emerged as significant problems [1]. These circumstances are in agreement with the observations made on the disregard, but the need, of the consideration of all cost and performance drivers early in the technology development process at low TRL including manufacturability to reduce development time, cost and risk and to achieve high techno-economic potential of the final product under commercial production and operation, led to the development of the Technology Performance Levels (TPL) [2], [3].

To address these issues Department of Defense (DoD) of the United States created the Manufacturing Readiness Level (MRL) Deskbook, a document where it is described how MRL criteria should be used in conducting assessments of manufacturing maturity and suggests how such assessments should be carried out.

This report focuses in assessing the supply chain and MRL for the large scale deployment of the innovative breakthroughs developed in the WETFEET project which involve innovative components. These breakthroughs are the dielectric generators, the structural membrane and the turbines as power-take-off – a tetra-radial air turbine for the OWC and a water turbine. Nevertheless, the supply chain of other breakthroughs is also assessed.

1.1. MRL assessments

The deskbook developed by the DoD establishes target maturity criteria for measuring risks associated with manufacturing processes and their MRL levels. However, quantitative assessments are necessary to determine whether these criteria have been met.

Assessments of manufacturing readiness utilizing the Manufacturing Readiness Level criteria have been designed to manage manufacturing risk in acquisition while increasing the ability of the technology development projects to transition new technology to weapon system applications. In the case of the WETFEET project, the MRL criteria is applied to energy systems with due modifications, which include selecting the appropriate risk areas to be analyzed.

MRL criteria create a measurement scale and vocabulary for assessing and discussing manufacturing maturity and risk. Using the MRL criteria, an assessment of manufacturing readiness is a structured evaluation of a technology, component, manufacturing process, system or subsystem. It is performed to:

- Define current level of manufacturing maturity;
- Identify maturity shortfalls and associated costs and risks;
- Provide the basis for manufacturing maturation and risk management.

Manufacturing readiness and technology readiness go hand-in-hand. MRLs, in conjunction with Technology Readiness Levels (TRL), are key measures that define risk when a technology or process is matured and transitioned to a system. It is quite common for manufacturing readiness to be paced by technology readiness or design stability.

The MRL scales are made up of incremental steps that provide the criteria for judging the progress of a manufacturing R&D program toward full-fledged manufacturing. The primary definitions for the manufacturing readiness levels are given in Table 1-1.

TABLE 1-1 MANUFACTURING READINESS LEVELS

MRL	Definitions
1	**Manufacturing Feasibility Assessed** – Top level assessment of feasibility based on technical concept and laboratory data.
2	**Manufacturing Concepts Defined** – Initiate demonstration of feasibility of producing a prototype system or component.
3	**Manufacturing Concepts Developed** – Manufacturing concepts identified and based on laboratory studies
4	**Laboratory Manufacturing Process Demonstration** – Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Targets set for cost as an independent variable, and initial cost drivers identified.
5	**Manufacturing Process Development** – Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.

6	**Critical Manufacturing Process Prototyped** – Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.
7	**Prototype Manufacturing System** – Prototype system built on soft tooling, initial sigma levels established. Ready for Low Rate Initial Production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production. Manufacturing process and procedures initially demonstrated. Design to cost goals validated.
8	**Manufacturing Process Maturity Demonstration** – Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).
9	**Manufacturing Processes Proven** – Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met). Actual cost model developed for Full Rate Production (FRP) environment, with impact of continuous improvement. Full rate process control concepts under development. Training and budget plans in place for transition to full rate production.
10	**Full Rate Production demonstrated and lean production practices in Place** – The system, component or item is in full rate production. Technologies have matured to at least TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. System, components, or items are in full rate production and meet all engineering, performance, quality, and reliability requirements. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to appropriate quality level. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

The aim of the WETFEET project is to raise the breakthrough technologies TRL from concepts and its applications (TRL 2), by proving its operability and validity by testing them individually in the laboratory (TRL 3) and applied to small scale WEC prototypes in a wave tank (TRL 4). Following this stablished objective, the MRL expected for the breakthroughs is around MRL 3 to 4.

Each MRL is further broken down into risk elements, which identify nine specific risk areas to be assessed for progressing from one MRL to the next. The risk elements are consistent for all the MRLs, but the assessment questions for each of the risk elements demand a more sophisticated manufacturing capability as the MRL advances.

A total of nine MRL threads have been defined to organize the dimensions of the manufacturing risk areas. The threads are as shown in Table 1-2.

TABLE 1-2 MRL THREADS AND DEFINITIONS

MRL Threads	Definition
A - Technology and the Industrial Base	Requires an analysis of the capability of the technology and industrial base to support the design, development, production, operation, uninterrupted maintenance support of the system and eventual disposal (environmental impacts).
B - Design	Requires an understanding of the maturity and stability of the evolving system design and any related impact on manufacturing readiness.
C - Cost and Funding	Requires an analysis of the adequacy of funding to achieve target manufacturing maturity levels. Examines the risk associated with reaching manufacturing cost targets.
D - Materials	Requires an analysis of the risks associated with materials (including basic/raw materials, components, semi-finished parts, and subassemblies)

E - Process Capability and Control	Requires an analysis of the risks that the manufacturing processes are able to reflect the design intent (repeatability and affordability) of key characteristics.
F - Quality Management	Requires an analysis of the risks and management efforts to control quality, and foster continuous improvement.
G - Manufacturing Workforce (Engineering and Production)	Requires an assessment of the required skills, availability, and required number of personnel to support the manufacturing effort
H - Facilities	Requires an analysis of the capabilities and capacity of key manufacturing facilities (prime, subcontractor, supplier, vendor, and maintenance/repair)
I - Manufacturing Management	Requires an analysis of the orchestration of all elements needed to translate the design into an integrated and fielded system (meeting Program goals for affordability and availability).

Not all the threads were assessed due to being out of the scope of the WETFEET project. The threads and sub-threads not considered are:

- Sub-thread C.3 – Manufacturing Investment Budget;
- Sub-thread D.4 – Special Handling of Materials;
- Thread F – Quality Management;
- Thread G – Manufacturing Workforce (Engineering and Production);
- Thread I – Manufacturing Management;

The assessment is made for each component by confronting what has been researched about it against a group of questions for each level and thread. Fulfilling the requisites of a certain level assure that the component belongs to the correspondent MRL.

1.2. WETFEET breakthroughs

The overall objective of the WETFEET project is to address and provide answers to identified engineering and technology-related issues and to the broader challenges of new wave energy converters, by developing wave energy ‘breakthrough items’, i.e. components, systems and processes, as well as the respective IP.

The WETFEET project objective is building upon a group of breakthrough concepts associated to the OWC spar buoy and the Symphony, with tailor-made engineering reasoning developed to examine the feasibility and potential of each breakthrough concept.

To do this, practical aspects related to the turning of the breakthrough concepts into use at large-scale applications have been examined and critical requirements for manufacturing, assembly, installation and the associated supporting machinery are highlighted.

2. MRL and Supply chain assessments

In the context of the WETFEET project, the Manufacturing Readiness Level of the different breakthroughs is to be assessed as part of WP7: Multi-disciplinary assessment for large scale deployment. The following sections will describe each breakthrough, identifying the elements that were assessed, the entities which are responsible for these elements, the manufacturing readiness for each element, areas where manufacturing readiness falls short of the target MRL criteria and which risk areas need further development in order to achieve a target MRL 4.

2.1. Structural Membrane

The structural membrane is the key innovative feature of the Symphony concept, solving the connection between the prime mover and its reference body. It acts as seal to enclose the inner pressure/volume and as bearing for the outer cylinder. In a way the membrane provides the variable volume ‘breathing’ under the waves.

An engineering choice with significant importance for future up-scaling plans is the membrane’s material, as it needs to have specific characteristics, reasonable costs and long-term availability in large quantities. The latter aspect is important to consider at an early stage, due to the key functions of the membrane for this type of WEC, and the need for substantial testing in controlled environment in the prototype phase. Thus it becomes of great importance to be able to transfer the prototype results into later developments.

Due to the central importance of the membrane for the overall viability of submerged pressure variation devices, the expert company in the field of polymer solutions, Trelleborg Ridderkerk, has been invited into the consortium with the specific task to design, manufacture build and test an upper and lower structural membrane as one of the breakthroughs for a Symphony WEC with a diameter of 1500 mm.

The membrane specifications are set by Teamwork Technology. Material properties, processing and fixing part of the design process are studied in WP3. The materials chosen for the membranes are Aramid cord reinforcement and Natural Rubber sealing, which final form is an Aramid fiber reinforced rubber, produced by Trelleborg, which is considered the supplier of the material.

In this case, the study of this breakthrough is detailed in deliverables 2.2, 2.3, 3.6 and 3.7, and will be complemented with the planned techno-economic assessment included in work package 7.

As can be seen in Table 2-1, the Structural Membrane shows an overall medium MRL, with the thread with the lowest MRL being the *Cost & Funding.*

TABLE 2-1 MANUFACTURING READINESS LEVEL OF THE STRUCTURAL MEMBRANE

Threads	Sub-Threads	MRL
A- Technology and Industrial Base	**A.1 - Industrial base**	5
	A.2 - Manufacturing Technology Development	4
B - Design	**B.1 - Producibility Program**	4
	B.2 - Design Maturity	4
C - Cost & Funding	**C.1 - Production Cost Knowledge (Cost modeling)**	3
	C.2 - Cost Analysis	3
D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems)	**D.1 - Maturity**	5
	D.2 - Availability	5
	D.3 - Supply Chain Management	5
E - -Process Capability & Control	**E.1 - Modeling & Simulation (Product & Process)**	6
	E.2 - Manufacturing Process Maturity	6
	E.3 - Process Yields and Rates	4
H - Facilities	**H.1 - Tooling / Special Test and Inspection Equipment (STE/SIE)**	5
	H.2 - Facilities	6

In order to achieve MRL 4 in the *Cost & Funding* thread, the study of this breakthrough would have to answer the following questions:

- Regarding *Production cost knowledge*:

  1. Have key manufacturing, material and specialized requirement cost drivers been identified?

  2. Are detailed process chart cost models driven by process variables?

- Regarding *Cost analysis*:

1. Have producibility cost risks been assessed?

2. Do initial cost models support Analysis of Alternatives (AoA) and Alternative Systems Review (ASR)?

In this case, the questions related with *Production cost knowledge* are expected to be answered in deliverable 7.3.

2.2. Dielectric Elastomer Generators (DEG)

Dielectric Elastomer Generators (DEGs) are a promising technology that could provide the breakthrough required by the wave energy sector.

DEGs are highly deformable capacitors (with deformations over 100%), made by elastomeric dielectric membranes coated with compliant electrodes, which can be used to convert mechanical energy into electricity and vice-versa. They operate via the variable capacitance electrostatic generation principle, thereby increasing the voltage of the charges that lie on DEG electrodes as the deformation in area of the DEG decreases.

The potential advantages of DEGs over conventional and competing technologies are: large energy densities (100-700J/kg); direct-drive and cyclic operation; good and rate-independent efficiencies (30-80%); moderate/low cost (5-15€/kg); good shock and corrosion resistance; easy manufacturability, deployment and disposal; silent operation; solid-state embodiment with self-sensing capabilities.

The assessment of this breakthrough was divided in two systems, which are the Elastomeric unit and the Power, Sensing & Controlling System.

Regarding the DEG material itself, a lot of research has already been done. The PolyWEC project has carried out pioneering research that demonstrated the feasibility and put the basis for the future development of this type of WECs. PolyWEC gathered a highly focused multidisciplinary research group which was able to study and produce innovations on materials, design, economic and environmental aspects of this new technology.

The necessary further research regarding the Elastomeric unit has been conducted by the partner Universität Linz (JKU of Linz), and is presented in deliverables 2.1, 2.2, 2.3 and 5.1. This info is complemented by the PolyWEC project deliverables and documents.

The material studied in the WETFEET project are the “VHB 4905” Acrylic elastomer from the company 3M, and two natural rubber materials, which are the "ZruElast A1040", from Zrunek Gummiwaren GmbH, and the "Oppo Band 8003" from Oppo Medical Inc.

Regarding the Power, Sensing and Controlling (PSC) System, the responsible for the study was the partner Scuola Superiore di Studi Universitari e di Perfezionamento Sant'anna (SSSA), and all the technical information is mainly presented in the deliverable 5.2, and the economic information planned for WP7. The PSC System is also considered innovative, although the materials and sub-components studied are mature technology.

As can be seen in Table 2-2, both systems show an overall medium MRL, no lower than level 3. The Elastomeric units lowest MRL is in the *Process Yields and Rates* sub-thread. Regarding the PSC system, it is the system with the most sub-threads evaluated as MRL 3. These low MRL results are in the *Design Maturity*, *Production Cost Knowledge* and *Materials Availability* sub-threads.

TABLE 2-2 MANUFACTURING READINESS LEVEL OF THE ELASTOMERIC UNIT AND THE POWER, SENSING AND CONTROL SYSTEM

Threads	Sub-Threads	MRL	
		Elastomeric Unit	**PSC System**
A- Technology and Industrial Base	**A.1 - Industrial base**	5	4
	A.2 - Manufacturing Technology Development	4	5
B - Design	**B.1 - Producibility Program**	4	4
	B.2 - Design Maturity	4	3
C - Cost & Funding	**C.1 - Production Cost Knowledge (Cost modeling)**	4	3
	C.2 - Cost Analysis	4	4
D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems)	**D.1 - Maturity**	6	4
	D.2 - Availability	5	3
	D.3 - Supply Chain Management	4	5
E - Process Capability & Control	**E.1 - Modeling & Simulation (Product & Process)**	6	6
	E.2 - Manufacturing Process Maturity	5	4
	E.3 - Process Yields and Rates	3	4
H - Facilities	**H.1 - Tooling / Special Test and Inspection Equipment (STE/SIE)**	5	5
	H.2 - Facilities	5	5

Regarding the Elastomeric Unit, in order for it to achieve MRL 4 in the sub-thread *Process Yields and Rates* the following issues would have to be studied:

1. Has a yield and rates assessment on proposed/similar processes been completed?

2. Has a yield and rates assessment on proposed/similar processes been applied within the Analysis of Alternatives (AoA)?

Regarding the PSC system, in order to achieve MRL 4, the study of this breakthrough would have to answer the following questions positively:

- Regarding *Design Maturity*:

  1. Do the Systems Engineering Plan (SEP) and the Test and Evaluation Strategy recognize the need for the establishment/validation of manufacturing capability and management of manufacturing risk for the product lifecycle?

  2. Have initial potential Key Performance Parameters (KPPs) been identified for the preferred systems concept?

  3. Are system characteristics and measures to support required capabilities identified?

  4. Are form, fit, and function constraints and manufacturing capabilities identified for the preferred systems concepts?

- Regarding *Production cost knowledge*:

  1. Have key manufacturing, material and specialized requirement cost drivers been identified?

  2. Are detailed process chart cost models driven by process variables?

  3. Has cost driver uncertainty been quantified?

- Regarding *Material Availability:*

  1. Have projected lead times been identified for all difficult to obtain, difficult to process, or hazardous materials?

  2. Have material quantities and lead times been estimated?

2.3. Tetra-radial air turbine for the OWC

The new tetra-radial turbine was conceived to solve the shortcomings presented by twin unidirectional turbines in oscillating water column (OWC) applications. The efficiency of the twin unidirectional turbine is negatively affected by one of the twin turbines absorbing a non-insignificant part of the total flow while consuming some power that would otherwise be available for conversion in the generator (due to negative torque)[4]. For this reason, the novel tetra-radial air turbine has been proposed as a PTO system for wave energy conversion.

The new tetra-radial turbine consists of two sets of rotor blades mounted on a common shaft and axially offset from each other. Each set of rotor blades is complemented by a set of guide vanes, as in a conventional unidirectional turbine. This whole set of rotor blades and guide vanes (stator) may be regarded as forming two conventional single-stage turbines.

The partner responsible for the development of this breakthrough is Instituto Superior Técnico (IST), and the information is found in deliverables 2.3 and 4.1, being that some research is ongoing in WP4 and WP7.

As can be seen in Table 2-3, the Tetra-radial air turbine breakthrough shows an overall medium MRL, with no thread below MRL 4.

TABLE 2-3 MANUFACTURING READINESS LEVEL OF THE TETRA-RADIAL AIR TURBINE

Threads	Sub-Threads	MRL
A- Technology and Industrial Base	**A.1 - Industrial base**	5
	A.2 - Manufacturing Technology Development	4
B - Design	**B.1 - Producibility Program**	4
	B.2 - Design Maturity	4
C - Cost & Funding	**C.1 - Production Cost Knowledge (Cost modeling)**	4
	C.2 - Cost Analysis	5
D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems)	**D.1 - Maturity**	5
	D.2 - Availability	5
	D.3 - Supply Chain Management	5
E - -Process Capability & Control	**E.1 - Modeling & Simulation (Product & Process)**	6
	E.2 - Manufacturing Process Maturity	4
	E.3 - Process Yields and Rates	4
H - Facilities	**H.1 - Tooling / Special Test and Inspection Equipment (STE/SIE)**	5
	H.2 - Facilities	5

2.4. Water turbine for the Symphony

The operational nature of the Symphony induces some unconventional requirements for the turbine. An oscillating force pushes the piston down. In one instance, a strong force is exerted, which reduces significantly for several seconds. Due to these sharp force variations, the pressure rise in the air spring tank is strong enough to push the piston upwards during the low force period. If the flow of the water is synchronised, the water oscillates between the piston and air spring tank. In the theoretical case of the oscillation being without losses, the pressure rise in the air spring tank would increase during every oscillation, due to resonance. By placing a turbine between the two components, the motion is damped. In equilibrium conditions, the turbine extracts the amount of energy that is added by the piston. If the turbine extracted all fluid energy from the flow, the oscillation would stop. Furthermore, the turbine must extract energy in two directions., has shown inFigure 1.

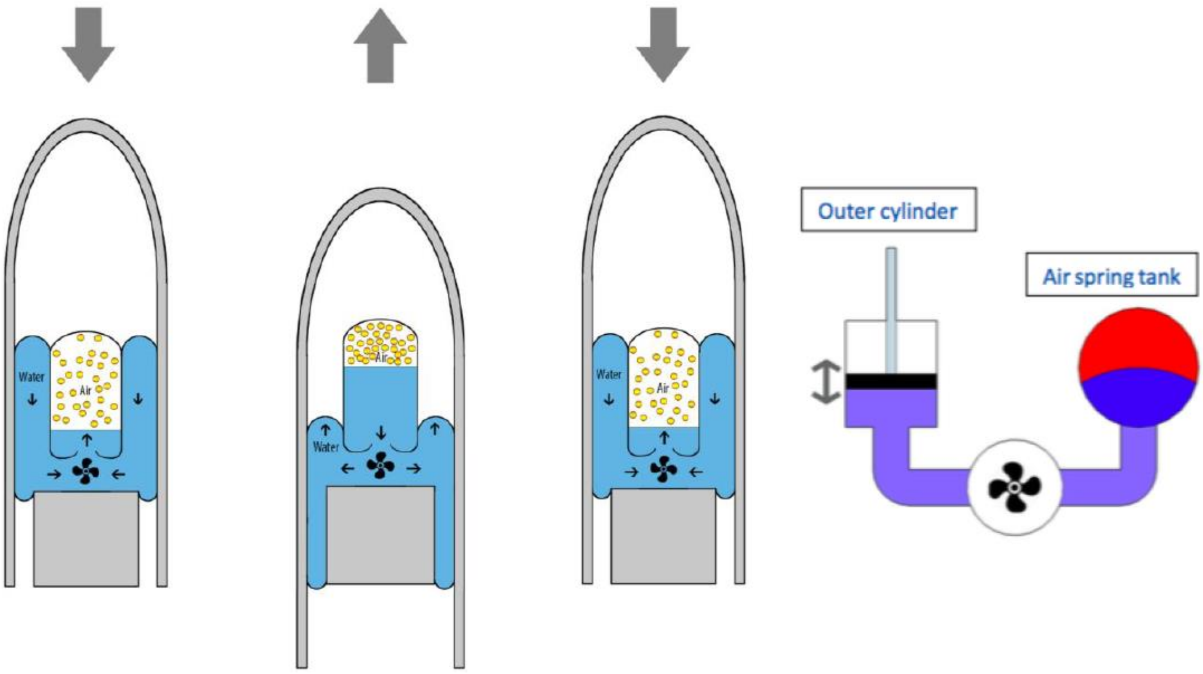

FIGURE 1 - OPERATIONAL PRINCIPLE OF WATER TURBINE IN SYMPHONY (LEFT) AND TEST BENCH/LABORATORY SETUP VISION FOR CONTROLLED TESTING OF PROTOTYPE (RIGHT)

There is no off-the-shelf solution for these operational requirements, which is why a novel water turbine as part of the power take off for a Symphony WEC has to be developed. The turbine will be engineered, manufactured and tested within WP4 of the WETFEET project, using the Symphony WEC as a reference basis. Focus was given on the design and building a prototype of the water turbine for a 1.5m diameter Symphony, and considerations for a full-scale device are included as a secondary objective.

This breakthrough is part of WP4, and the partner responsible for the development is Teamwork Technology, who have designed and patented the turbine, following the specifications set in deliverable 2.3.

As can be seen in Table 2-4, the Water turbine breakthrough shows an overall medium MRL, with no thread achieving below MRL 3.

Table 2-4 Manufacturing Readiness Level of the Water turbine

Threads	Sub-Threads	MRL
A- Technology and Industrial Base	**A.1 - Industrial base**	5
	A.2 - Manufacturing Technology Development	4
B - Design	**B.1 - Producibility Program**	5
	B.2 - Design Maturity	4
C - Cost & Funding	**C.1 - Production Cost Knowledge (Cost modeling)**	4
	C.2 - Cost Analysis	4
D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems)	**D.1 - Maturity**	4
	D.2 - Availability	3
	D.3 - Supply Chain Management	4
E - -Process Capability & Control	**E.1 - Modeling & Simulation (Product & Process)**	6
	E.2 - Manufacturing Process Maturity	4
	E.3 - Process Yields and Rates	3
H - Facilities	**H.1 - Tooling / Special Test and Inspection Equipment (STE/SIE)**	4
	H.2 - Facilities	4

In order to achieve MRL 4, the study of this breakthrough would have to answer the following questions positively:

- Regarding Process Yields and Rates:

  1. Has a yield and rates assessment on proposed/similar processes been completed?

  2. Has a yield and rates assessment on proposed/similar processes been applied within the Analysis of Alternatives (AoA)?

- Regarding *Material Availability:*

1. *Have projected lead times been identified for all difficult to obtain, difficult to process, or hazardous materials?*

2. *Have material quantities and lead times been estimated?*

2.5. Other

The MRL assessment was not made for the other breakthroughs which had involved no innovative components. However, the supply chain assessment was performed by sub-dividing the system into components, and some considerations regarding their manufacturing processes was made.

For the breakthroughs related to the OWC, the following division and considerations are relevant:

- Negative Spring – For this breakthrough, the Hydrodynamic Negative Spring was studied regarding its feasibility and there was no design of innovative components.
- Enhanced Added Mass – Only an improved structure shape with no manufacturing challenge was studied, involving no innovative components.
- Survivability Submergence – For this breakthrough there is no conception of innovative components. However, due to limited subsea winch capacity, a need for stronger subsea winches is identified. Alternatively, a system composed of 4 existing subsea winches is studied. The pumping system, valves, energy supply, anchors, solutions to ensure cable integrity, reinforcement of the hull, automation/SCADA/sensors system and the signalization system are either off-the-shelf models, or partly custom made or no challenge is foreseen in its implementation.
- Shared Moorings - For this breakthrough there is only an improved structure configuration, no innovative components are designed or identified.

For the breakthroughs related to the Symphony, the following division and considerations are relevant:

- Continuous Submergence – For this breakthrough, there are also no innovative components, further than the submergible turbine, studied in another breakthrough. The generator and converter are off-the-shelf models and exemplary models are identified. The seals, valves and connectors of the electronics and control system are partly custom-made items with special requirements. The spring adjustment tank is not part of the design steps in this phase, as it is considered an uncritical item, which can be adjusted and manufactured according to available space and configuration inside the cocoon. The compressed air tank is in a pressure range common for off-the-shelf pressurized air tank systems;

- Shared Moorings (Compact aggregates) – For this breakthrough there is only an improved structure configuration, with no innovative components designed or identified. The mooring system components are off-the-self, and exemplary models and suppliers are identified.

3. Conclusion

3.1. Results

The results of the Manufacturing Readiness Level assessment show that the WETFEET breakthroughs have been studied widely and deeply enough to achieve overall satisfying results regarding the MRL objective.

The aim was to bring the systems to Technology Readiness Level 3-4, and thus the MRL to the same level. With this initial MRL assessment, what can be seen is a generally higher MRL level than expected, which would be around MRL 4. Table 3-1 summarizes the results of the MRL assessment for comparison.

TABLE 3-1 OVERALL RESULTS OF THE MRL ASSESSMENT

		Structural membrane	DEG		Water turbine	Tetra-radial air turbine
			Elastomer unit	PSC system		
A- Technology and Industrial Base	A.1 - Industrial base	5	5	4	5	5
	A.2 - Manufacturing Technology Development	4	4	5	4	4
B - Design	B.1 - Producibility Program	4	4	4	5	4
	B.2 - Design Maturity	4	4	3	4	4
C - Cost & Funding	C.1 - Production Cost Knowledge	3	4	3	4	4
	C.2 - Cost Analysis	3	4	4	4	5
D - Materials (Raw Materials, Components, Sub-assemblies and Sub-systems)	D.1 - Maturity	5	6	4	4	5
	D.2 - Availability	5	5	3	3	5
	D.3 - Supply Chain Management	5	4	5	4	5
E - -Process Capability & Control	E.1 - Modelling & Simulation	6	6	6	6	6
	E.2 - Manufacturing Process Maturity	6	5	4	4	4
	E.3 - Process Yields and Rates	4	3	4	3	4
H - Facilities	H.1 - Tooling / Special Test and Inspection Equipment	5	5	5	4	5
	H.2 - Facilities	6	5	5	4	5

The Manufacturing Readiness for the Tetra-radial turbine is the most advanced of the manufacturing capabilities assessed, with no result under MRL 4.

The Water turbine was the breakthrough assessed with the lower manufacturing capabilities overall, reaching MRL 3 in two risk areas, followed by the PSC system of the Dielectric Elastomeric Generator, which reached MRL 3 in 3 risk areas.

The risk area with the higher results, meaning less risk, is the *Modelling & Simulation* sub-thread with overall results of MRL 6. This is a very positive result which can be consequence of the high expertise and research focus of the involved partner organizations.

The *Production Cost Knowledge* and *Process Yields and Rates* risk areas had the lowest results in general, between MRL 3 and 4. This means more focus must be given to this areas in order to progress the MRL in the future. These results are still considered satisfying for the objective MRL of the WETFEET project.

Regarding the Structural Membrane system, only the Cost & Funding risk area needs further analysis. This analysis is expected to be done in deliverable 7.3 for this breakthrough as well as, in some extent, for the other breakthrough technologies.

Regarding the DEG breakthrough, composed by the Elastomeric unit and the Power, Sensing and Controlling system, more research has to be done in different areas in order to achieve the target minimum MRL 4. To achieve this, further research must be developed, such as the completion of process yield and rates assessment, the recognizing of the need for the establishment/validation of manufacturing capability and management of manufacturing risk, the identification of key manufacturing, material and specialized requirement cost drivers, quantifying cost driver uncertainty, and also to estimate material quantities and lead times.

The Tetra-radial air turbine, being the breakthrough with the highest MRL level and having no risk area with results below MRL 4, already attains the target MRL and needs no further research to be developed.

Regarding the Water turbine, it is the breakthrough with the lowest overall MRL result. In order to raise the result and reduce risk, further research would have to be completed, addressing issues such as the assessment of process yield and rates and estimating quantities and lead times.

Regarding the other breakthroughs, they do not involve innovative components so an MRL assessment was not conducted for them. These systems or components are either off-the-shelf models, or partly custom made or no challenge is foreseen in their implementation.

3.2. Recommendations

The Manufacturing Readiness Assessment provides an assessment of the progress of a manufacturer toward Low Rate Initial Production (LRIP) and Full Rate Production (FRP) for a given market segment, using a standard methodology that can lead to comparative and agglomerate analysis of the industry. The evaluation of LRIP for an emerging market and the assessment of a manufacturer's ability to produce at LRIP can be used as "jump-in"/ "jump-out" criteria for decision makers. An ongoing MRL assessment activity should be established to support the sectors market transformation activity. Participation in this activity should be a requirement for all co-funded demonstration activities, so that unbiased, comparative assessments can be made.

In order for the breakthroughs to have a higher and more complete MRL, the other risk areas not considered in this assessment should be studied and assessed in order to lower the risk associated with the manufacturing processes. These risk areas include *Quality Management, Manufacturing Workforce (Engineering & Production)* and *Manufacturing Management.*

Regarding the timing of the MRL assessment, it should be revised later in the project, when the study of all technical and economic matters has been performed, in order to have complete information about the technologies and components.

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