DIGItal MANufacturing and Proof-of-Process for Automotive Fuel Cells

DELIVERABLE REPORT D2.3
WP2 INTERIM REPORT

Authors:

REVISIONS			
Version:	**Date:**	**Changed by:**	**Comments:**
1.0	25 July 2018	Tony Wilson (IE)	Draft
2.0	06 September 2018	Tony Wilson (IE)	Submitted Version

DIGItal MANufacturing and Proof-of-Process for Automotive Fuel Cells

Grant agreement no.: 736290
***Start date**: 01.01.2017 – **Duration**: 36 months*
***Project Coordinator**: CEA Tech - LITEN*

Deliverable Report D2.3

D2.3 – WP2 Interim Report	
Due Date	July 2018
Author(s)	Tony Wilson (IE)
Work Package	2
Work Package Leader	Isotta Cerri – TME
Lead Beneficiary	
Date released by WP Leader	
Date released by Coordinator	06/09/2018

Dissemination Level		
PU	*Public*	***Y***
PP	*Restricted to other programme participants (including the Commission Services)*	
RE	*Restricted to a group specified by the consortium (including the Commission Services)*	
CO	*Confidential, only for members of the consortium (including the Commission Services)*	

Nature of the Deliverable		
R	*Report*	***Y***
P	*Prototype*	
D	*Demonstrator*	
O	*Other*	

SUMMARY	
Keywords	*Automotive best practise, key performance indicators, delivered stack performance, performance of production system*
Abstract	*DigiMan's Work Package 2 involves the setting of requirements for i) the attainment of AC64 fully automated fuel cell stack assembly, and ii) demonstration of that attainment to MRL6 - capability to produce a prototype system or subsystem in a production relevant (i.e. automotive) environment. From this, metrics & target KPIs will be derived. End-of-line (EOL) stack test method procedures and processes will be derived to meet customer performance baselines. This Interim Report provides a mid-term review and status update for the work package.*
Public abstract for the public website (only for confidential deliverables)	*DigiMan's Work Package 2 involves the setting of requirements for i) the attainment of AC64 fully automated fuel cell stack assembly, and ii) demonstration of that attainment to MRL6 - capability to produce a prototype system or subsystem in a production relevant (i.e. automotive) environment. From this, metrics & target KPIs will be derived. End-of-line (EOL) stack test method procedures and processes will be derived to meet customer performance baselines. This Interim Report provides a mid-term review and status update for the work package.*

REVISIONS

Version	**Date**	**Changed by**	**Comments**
1.0	25/07/2018	Tony Wilson (IE)	First Issue
2.0	06/09/2018	Tony Wilson (IE)	Submitted Version

DELIVERABLE 2.3
WP2 INTERIM REPORT

CONTENTS

Nomenclature

Symbol or acronym	Description
TME	Toyota Motors Europe
IE	Intelligent Energy
OEM	Original Equipment Manufacturer
VoC	Voice-of-the-Customer
PEMFC	Proton Exchange Membrane Fuel Cell
AC	Air Cooled
GDL	Gas Diffusion Layer
PoP	Proof-of-Process
QC	Quality Control

1. INTRODUCTION

The DigiMan project aims to develop a blueprint design for next generation cell assembly and testing of Intelligent Energy's current and future lightweight AC fuel cell stack technology. Core to the project's objectives is the development of this production capability via the uplifting of pre-existing semi-automation.

Specific targets are:

- Demonstrate, via the uplifted automation, a blueprint design to scale to production capacity >50,000 stacks/year by 2020
- Demonstrate for a single production line, an aggregated total stack power output of >5MW
- Demonstrate a cycle time step improvement from >22 secs (semi-auto single loop production line) to <5 seconds assembly per cell (x5 times uplift)
- Advance the stack manufacturing technology level from MRL4 to MRL6
- Develop in-process quality controls at component and sub-component level to reduce scrap rate to target <3%
- Model costs showing target trajectories consistent with automotive targets for 2020 at 50k stacks per annum
- Ensure that the stack performance is not detrimentally affected by manufacturing and assembly improvements, IE delivering 0.7 A/cm2 @ 0.7V for world leading AC fuel cell technology

Specific objectives relating to this deliverable report are to:

- Deliver automated manufacturing maturity to fuel cell stack and components
- Embed quality in automotive stack production via uplifted automation in the form of a 'blueprint' reference design, as validated to MRL6 via proof-of-process demonstrator equipment and virtual simulations of a 'digital twin'
- Demonstrate automotive best practice, for example fixed rate flow lines with bypass loops for interrupt mitigation (intervention/buffering)

1.1 BACKGROUND

The DigiMan project's charter is to raise the manufacturing level for Intelligent Energy's AC64 AC stack technology from **MRL4 to MRL6**. It aims to advance the critical steps of the fuel cell assembly processes and associated in-line QC & end-of-line test / handover strategies. In doing so it will also demonstrate a route to automated volume process production capability within an automotive best practice context e.g. cycle time, optimisation and line-balancing, cost reduction and embedded / digital quality control.

Other work has so far included characterisation and digital codification of physical attributes of key materials (e.g. GDLs) to establish yield impacting digital cause and effects relationships within the value chain, from raw material supply / conversion / assembly through to in-service data analytics. This, aligns with evolving Industry 4.0 standards for data gathering and security, and line up-time / productivity monitoring. The expected outcomes will provide a blueprint for next generation automotive fuel cell manufacturing capability in Europe.

DigiMan exploits existing EU fuel cell and manufacturing competences and skill sets to enhance EU employment opportunities and competitiveness. DigiMan also supports emission and Carbon Dioxide reduction targets across the automotive sector as well as increased security of fuel supply by utilising locally produced Hydrogen. These benefits can also be applied to other industry applications which utilise IE's AC fuel cell technology, including stationary power and UAV markets.

1.2 WP 2 Objectives

This report relates to WP 2 (Requirement Setting & PoP Measurement) which involves the setting of requirements for i) the attainment of AC64 fully automated fuel cell stack assembly, and ii) demonstration of that attainment to MRL6 - capability to produce a prototype system or subsystem in a production relevant (i.e. automotive) environment. From this metrics & target KPIs will be derived. Also end-of-line (EOL) stack test method procedures and processes will be developed to a voice-of-the-customer expectation for stack handover performance baselines. Technical cost models will be reviewed and updated post PoP demonstration trials, which will scale and forecast costs for volume production of fuel cell AC64 stacks. This interim and a final report will be generated within this work package.

The high-level objectives are:

- Definition of the fuel cell stack performance at production handover for volume production targets that meet automotive standards, e.g. DIGIMAN target cycle time cell assembly < 5 secs, component yield >95%, material utilisation >99%
- Provide cost analysis summary resulting from the project outcomes

1.3 WP 2 Deliverables

Reporting of the deliverables for WP 2 is as follows:

- D2.1 Auto Best Practice & KPIs
- D2.2 Stack Beginning of Life Handover
- D2.3 Project Interim Report
- D2.4 End of Line Stack Test Methods
- D2.5 Cost Modelling

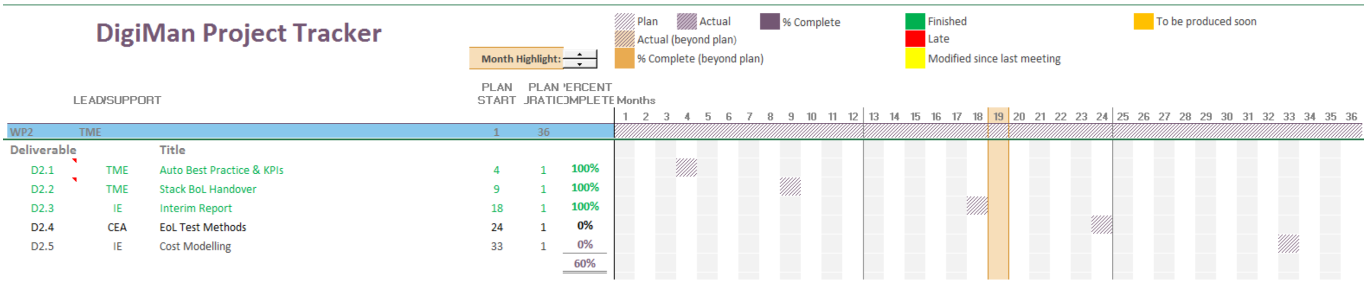

Figure 1 – WP 2 Deliverable Status

1.4 WP 2 Midterm Deliverable

As the third deliverable report under Work Package 2, D2.3 reports on:

- Task 2.1 Definition of Auto Best Practice & Specification of Baseline KPIs
- Task 2.2 Stack Commissioning and Handover Baseline Requirements
- Task 2.3 Stack End-of-line (EOL) Test Methods

Note: Task 2.3 commenced in the latter part of Period 1 but completes and fully reports in Period 2, as is the case with the following tasks:

- Task 2.4 Technical Cost Modelling - Stack Assembly
- Task 2.5 DigiMan Interim & Final Report

2. Description of Work

Requirement setting & PoP measurement involved the derivation and capture of deliverable targets to:

i) Capture VoC to support demonstration of the (to be developed) Blueprint design's deployment readiness (MRL6), within an automotive best practise context

ii) Demonstrate attainment of the project's key objectives via meeting the KPI targets for:
   a. Delivered fuel cell tack performance
   b. Performance of fuel cell stack production system

2.1 Automotive Best Practice

The objectives for WP2 derive from FCH-01.1-2016 work plan: 'Transpose established automotive industry best practices on production and quality to the manufacturing of PEMFC stack and stack components, such as (but not limited to) lean manufacturing, kaizen, six-sigma'. The work plan objective is addressed within Period 1 by capture of VoC best practice performance targets based on the Toyota Production System (TPS) and allow Quality Function Deployment (QFD) planning for the other below work plan objectives:

- 'Development of manufacturing technologies, beyond state of the art, specific to PEM stack production processes, equipment and tools'.
- 'Identification of bottleneck processes in stack or stack component production lines:'
- 'Identification and revision of critical sub-processes (e.g. low yield / high cost)
- 'Improvement, modification, adaptation or even new development of at least two critical stack or stack component production steps'
- 'Integration of in-line non-destructive quality controls'
- 'Adaptation of stack and/or stack component design to optimise manufacturability'
- 'Development of QA strategies relevant for the transportation sector compatible with ISO/TS16949'

Value Stream Analysis and visualisations will be used to show compliance with TPS's House of Quality philosophy with its jidoka and Just-in-Time pillars.

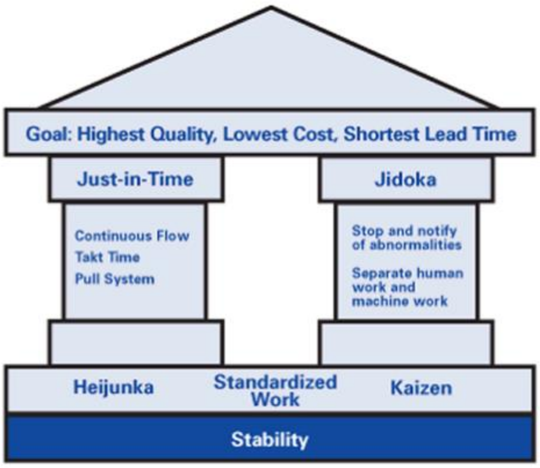

Figure 2 – The Toyota Production System House

From the TPS definitions DigiMan's other work packages will demonstrate the following:

- Lean manufacturing - methodologies have been developed in the form of line-side converting of components from roll-stock raw material, demonstrating automotive best practices with pull-demand (i.e. Kanban) for minimised, line-side inventory of raw material. This arrangement aids flexible, fast response job change-over (SMED – Single-Minute Exchange of Die). Thereby, benefiting production flow (addressing the TPS's Muri type waste).

- Continuous improvement - digital cause & effects relationship modelling is currently being developed and will be fully exploited within Period 2. Causation data will be mined from the developed digital characterisations of material physical attributes and codified by i) localised spot defects / blemishes and ii) homogeneity / structural none-conformities. Data rich sensing capability (of cause metrics) is being embedded within the fully automated assembly solution and digital converting equipment for GDL component production. This output will be complemented by big data sources derived, in part, from in-service functionality self-monitors as harvested via WP 6 activities. This will enable digital cause / effects modelling and offer knowledge based guidance for on-going opportunities for continuous improvement i.e. kaizen

- Six Sigma - DMAIC methodologies are served and an industry wide gap addressed in supply chain processes for the converting of imperfect roll-stock into pre-screened (known-good) and ready to assemble GDL components. These best practises are being codified and embedded within the under development Digital QC system. The Digital QC functionality will be enhanced, and progressively refined through linked digital cause / effects modelling, thus offering closed loop six-sigma implementation and control.

2.2 KPI's

2.2.1 Delivered FUEL CELL Stack Performance

Delivered fuel cell stack performance testing – Task 6.4 (Stack Manufacturing Validation Testing) involves functionality testing of beginning of life performance at handover from stack production to vehicle assembly. The fuel cell stacks will be assembly via the uplifted automation (i.e. the PoP Demonstrator equipment plus IE's incumbent fully automated cell test and stack assembly machines). In this way the 2016 Work Plan's target performance KPI's will be both demonstrable and measurable, and also provide the proof-of-process validation of the Blue-print design's MRL6 attainment.

The stack delivered performance KPI's are listed below for a typical 72-cell stack configuration:

Metric	Unit	KPI
Stack nominal gross power	kW	2.1
Rated Voltage	Vdc	52
Electrical efficiency, rated	%	54.5
Mass	Kg	2.9
Specific Power	W / kg	714
Power Density	W / L	726
Stack Environment	Deg C	+5 °C to +50 °C ambient
System Environment	Deg C	-40 °C to +50 °C ambient
Altitude	m	0 to 4000
Fuel composition	-	99.95% gaseous hydrogen or better

Table 1 – Delivered Stack performance KPIs – 72-cell

2.2.2 BLUE-PRINT MRL6 ATTAINMENT KPIS

Performance of stack production system

KPIs have been derived to benchmark specific and tangible performance metrics such as cycle time, assembly related costs, yields and uptime. Without them it would not have been possible to assess the uplifted automation's (i.e. fully automated cell assembly) capability. Via extensive trialling of the PoP demonstrator equipment and planned discrete event simulation, the Blueprint design's delivery of overall project key objectives, in a scaled volume production scenario would not be measurable. Therefore, the setting of baseline KPIs will allow the virtual simulation (via use of PoP demonstrator trial data) of production scale run-at-rate scenarios. These simulations, together with rigorously tested fuel cell stacks, as assembled via the uplifted automation (including pre-existing fully automated process stages) will constitute manufacturing validation (Task 6.4) and provide the evidence of attainment of MRL6.

The discrete event simulation will overlay lean manufacturing scenarios of Jidoka and Just-in-Time to demonstrate automotive best practice to the exacting standards of the TPS.

For the baseline production requirements see below, data based on a typical 72-cell stack:

Metric	Unit	KPI
Production rate in units/h	Stacks / h	10
Production rate in units/yr	Stacks / yr	60,000
Production rate in power/yr	MW / yr	120
Component yield	%	>95
Material utilisation	%	>99
Stack quality acceptance criterion	NA	Power, voltage, current, leak rate
Number of direct staff per number of units produced	Person / unit	1
Number of staff per MW power produced	Person / MW	0.025
Production line footprint (based on blue print-based design plus automated stack assembly based on IE existing design @ 5 secs Takt time)	M^2	28
Operational Efficiency (OEE - Overall Equipment Efficiency)	%	85
Manufacturing Readiness Level		From MRL4 to MRL6

Table 2 – Performance of Stack Production KPIs – 72 cell

3. WP 2– Mid-term Progress

The work package objectives to mid-term are addressed via:

- Completion of Task 2.1 - Definition of Auto Best Practice & Specification of Baseline KPIs.
- Completion of Task 2.2 - Stack Commissioning Handover Baseline Requirements
- Commencement of Task 2.3 - Stack End-of-line (EOL) Test Methods
- Drafting and issue of deliverable report D2.1 - Automotive Best Practice & KPIs
- Drafting and issue deliverable report D2.2 – Stack BoL Handover

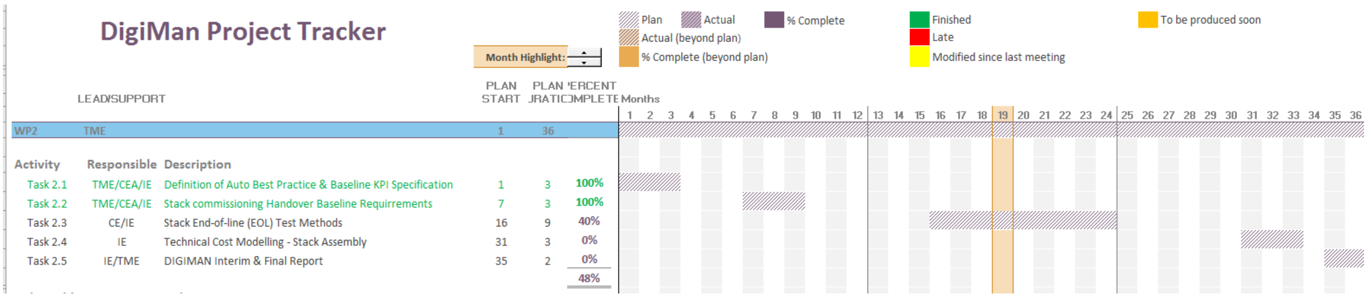

Figure 3 – WP 2 Midterm Task Status

No milestones apply directly to this work package but requirement setting & PoP measurement is a pre-requisite enabler for:

- MS1 - PoP Demo Requirements
- MS2 - PoP Demonstrator Designed

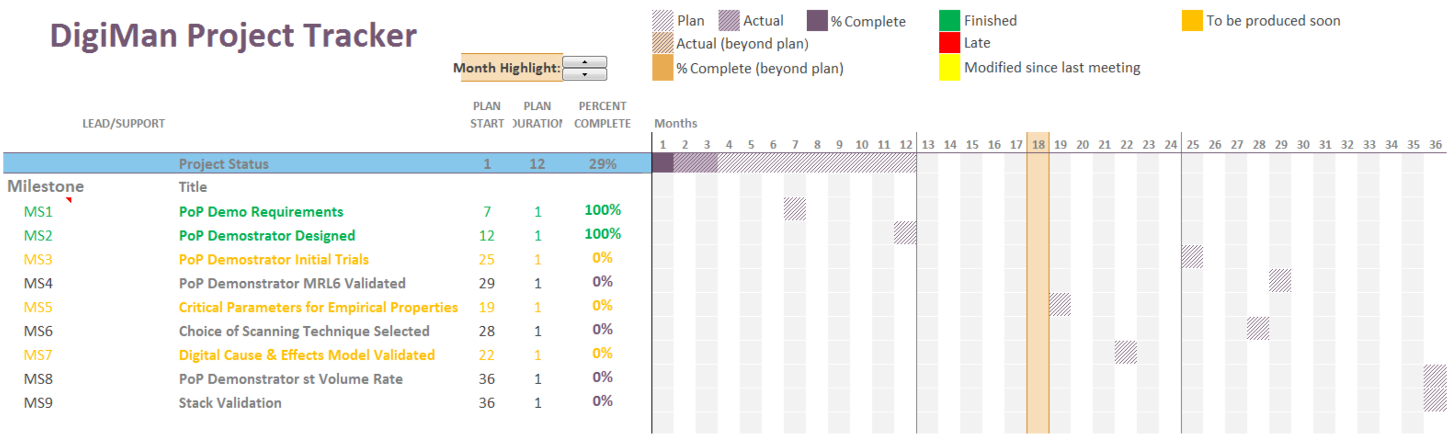

Figure 4 – DigiMan Mid-term Milestone Status

4. Future Work – WP 2 Period 2

Within WP2, the development of end-of-line (EOL) fuel cell stack test method procedures and process commenced in Period 1. This will carry over into Period 2 as originally scheduled and then input into WP2 delivery of technical cost models. Automation of stack connectivity to the test rig and incorporated conditioning / handover test communications within a single piece flow line offers possible alignment and harmonisation with typical auto maker's, at rate, single piece flow. This will be modelled, as direct-to-line drop-in / drive-off scenarios within WP2 Tasks 2.3 & 2.4 and reported on in D2.4 (EoL Test Methods), D2.5 (Cost Modelling) and D6.3 (Discrete Event Simulation).

4.1 Stack End-of-Line Test Methods

IE's previous developments around stack testing have focused on stack conditioning and test duration times as applicable to research and development activities. Historically, production volumes have been modest and stack QC handover testing has not been a bottleneck. Hence, a multi hour conditioning / handover test constituted the standard baseline test duration.

To address this throughput limiting disparity and establish factors which may correlate to accelerated handover test performance, Task 2.3 activities have included a sequence of stack design-of-experiments (DoE). These have enabled a significantly reduced duration stack conditioning / handover test, with this shortened test methodology trialled on a small sample of AC64 fuel cell stacks.

Further work is required to ensure that these factors are robust, relate to the latest generation of IE AC64 fuel cell stack technology and do not have a detrimental effect on the intended product application. This will be covered as continuation of Task 2.3 and reported upon within the Deliverable Report D2.4 at month 24. IE will interpolate performance, life expectancy, environmental compatibility and robustness of life targets for the AC64 fuel cellstack and derive a Beginning of Life test procedure, including leak rates and conditioning time as appropriate to the KPI acceptance criteria which were established within task 2.2. To minimise test duration times, differing conditioning phases will be evaluated. IE is targeting a total 30 minute functional and performance QC test as a replacement for the current multi hour duration test.

4.2 Technical Cost Modelling

Notwithstanding key performance benchmarking, fuel cell vehicle costs will come under intense scrutiny to compete with the incumbent technologies e.g. petrol / diesel / hybrid). Zero emission technologies are not guaranteed to be afforded a future price premium. Without uplifted technology, fuel cell stack assembly cost / volume scalability will be constrained and production volumes will only increase when automotive OEMs commit to the technology; something they are unlikely to do without a route to meeting vehicle cost targets.

The cost target projections within the FCH-JU Multi –Annual Work Programme 2014 – 2020 Table 3.1.1.1 are acknowledged and set the benchmark against which OEM €/kW targets will be measured under this programme. However, it is important to recognise that the stated targets within Table 3.1.1.1 relate to fuel cell primary power automotive applications, whereas DigiMan target KPIs relate to commercial affordability for automotive range extender deployment.

Application	Parameter	Unit	2012	FCH-JU target		
				2017	2020	2023
Fuel cell electric passenger cars	Specific FC system cost *Assumed number of units (per year) as cost calculation basis*	€/kW	>500	150 *20 000*	100 *50 000*	75 *100 000*
	FC Vehicle cost (C-segment)	k€	200	70	50	30
	Tank-to-wheel efficiency (vehicle in New European Drive Cycle)	%	40	42	45	48
	Availability	%	95	98	98	99
	FC system Lifetime	hours	2500	5000	6000	7000

Table 3 – FCH-JU Multi – Annual Work Programme 2014 – 2020 Table 3.1.1.1

Period 2 activities including development of the digital twin, will then allow the structuring of technical cost models as based on the Blueprint design (with lineside converting). Via discrete event simulations operational scenarios including operator counts, throughput, process yield, unplanned process interrupts and overall operation efficiency will factor into the costs modelling. The Blueprint design will be commercially quoted on a modular basis allowing the inclusion of capital expenditure and recovery / amortisation costs.

END OF REPORT