TECHNOLOGY READINESS OF SOFC STACKS – A REVIEW

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ABSTRACT

The concept of technology readiness levels (TRL) had become recently popular both in Europe and in Canada to evaluate the maturity of a technology or product. The classification is mandatory in the European Union Horizon2020 Research Program and in the Industry "Build in Canada" Innovation Program (BCIP).

The charming simplicity of the TRL1 to TRL9 classification helps to label the maturity of a certain product concept or technology, especially in the early phases of research and development. On the other hand, it gives no or very limited information about the actual technology readiness. To overcome this limitation, IKTS has adopted and refined the technology readiness evaluation of Solid Oxide Fuel Cell (SOFC) Stacks.

The fuel cell stack is the key building block in any fuel cell system. Over the years, Fraunhofer IKTS has developed three different SOFC stack concepts, one is commercialized by the company Sunfire in Germany, a second concept is used in eneramic® systems, and a third concept, the CFY stack technology, is about to be commercialized with other partners. The technology readiness evaluation outlined in this paper is using three sets of parameters – technical performance and lifetime parameters, manufacturing and value chain parameters, as well as a market segment definition and commercialization aspects.

It is used to compare stacks on the market or under development, and to measure progress over time. Thus, an indication of SOFC technology readiness, segment specific time to market and R&D needs was developed.

BACKGROUND

A systematic approach to evaluate technology readiness levels (TRL) had been developed by NASA in the 1980s as presented by John C. Mankins[1], and is practically the base for any TRL definition given by European Union[2] or the "Build in Canada Innovation Program" (BCIP).

The approach had been originally developed for one of a kind solutions in space technology, and is thus not well suited to estimate technology maturity of critical components or a new technology (key enabling technology) as used by European Union. Limitations are obvious, as the self-evaluated technology readiness is not linked to any actual technical parameters required for a successful commercial application, and manufacturing and cost aspects are not included in any way. Furthermore, regulatory aspects, customer perception and component or supply chain readiness define to a considerable extent, if a new technology will be successful.

In 2010, Reinhart et al.[3] published an approach to evaluate technologies with a special focus on manufacturing aspects. This basic idea has been adopted in the present work and has been modified towards a consistent technology readiness estimation. In contrast to the study by Reinhart et al., three basic fields for technology readiness have been chosen – a) technical readiness, b) manufacturing and supply chain readiness, and c) aspects of the cost and business model.

In each of these three sub-fields, qualitative or quantitative parameters were standardized to a percent scale, assuming 100 % representing the ideal or target value (either low or high). The single worst value defines the overall readiness in the fields a) to c). The mean value of readiness parameters from fields a) to c) may be considered as the calculated technology readiness level. Suggested percent values for the classification of a technology's maturity status are correlated to common TRL definition as shown in Table 1 below.

Table 1. Suggested percent values for TRL calculation and correlation to common TRL definition.

Scale of Technical Maturity	Percent Value	TRL
Basic principles	1 %	1
Concept or application formulated	10 %	2
Analytical or experimental proof of concept	20 %	3
Key component breadboard validation in lab	30 %	4
Key component breadboard validation in field	40 %	5
System validation in lab	50 %	6
System validation in field	60 %	7
Field testing positively ongoing	80 %	8
Field-proven commercial product	100 %	9

The actual calculation of readiness levels in the sub-fields a) to c) as illustrated in detail further below is also different to Reinhardt et al. The herein presented approach is considered more logical, assuming that the single worst parameter is defining whether the product or technology will work or fail. In order to prioritize different assessment parameters, e.g. for various market segments or applications, an optional weight factor was included as well. The basic approach is explained in detail below and applied to SOFC stacks.

ADVANCED CONCEPT FOR TRL ESTIMATION – APPLIED TO SOFC STACKS

To evaluate the Technology Readiness of Fuel Cell systems – herein delimited to Solid Oxide Fuel Cell (SOFC) systems – the primary focus should be on the SOFC stack for a couple of reasons. First, the SOFC stack is the key element of any SOFC system, as sketched in the schematic boundary diagram in Figure 1 below, and accounts for 30 to 50 % of system cost.

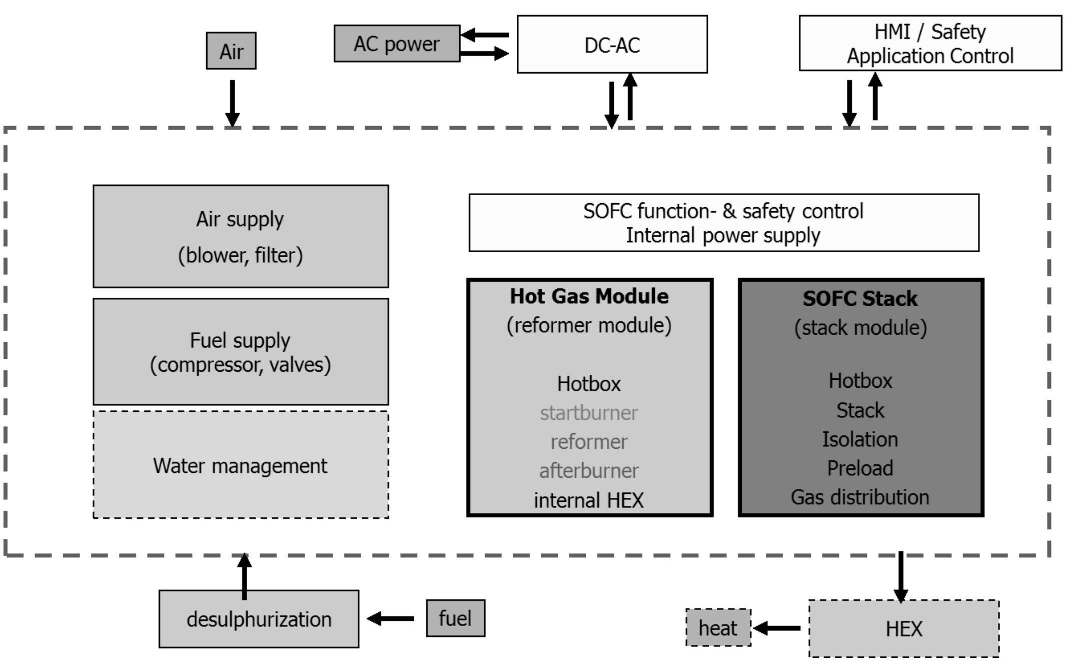

Figure 1. Generic boundary diagram of a SOFC system.

Secondly, the SOFC stack is a demanding combination of high temperature materials (ceramics, steels, glasses) and its development requires a unique combination of electrochemistry, material science, electrical, process and mechanical engineering skills, which can hardly be found in this combination in any other product. Therefore, there are no industrial standard equipment manufacturers available and no supply chain is established, so far. Today, the SOFC stack performance limits the efficiency and durability of most systems currently installed in the field.

Fraunhofer IKTS has developed over the last two decades three different SOFC stack concepts based on planar, electrolyte supported cells (ESC). One was transferred to a commercial supplier staxera GmbH (today Sunfire GmbH) and the two others are currently in the transition phase to commercialization. Thus, the institute is in a unique position to evaluate the different stack technologies with regard to their technical maturity. In this paper, two recently developed stack technologies are evaluated. Sample views of a CFY stack and an eneramic® stack are shown in Figure 2 below.

Figure 2. Sample views of CFY stack (left, mounted in handling device, footprint 15 x 13 cm), and eneramic® stack (right, with transport lock, footprint 7 x 7 cm).

In the CFY stack, the interconnect material (powder processed Chromium/Iron-alloy of Plansee SE) and cell type (Scandia doped ESC) differs significantly from the ferritic steel sheet metal interconnect in combination with partially yttrium stabilized zirconia (3YSZ) cells in the eneramic® stack. Detailed technical reports about the design, development and performance of the stacks have been published elsewhere[4, 5].

The technology readiness is evaluated for three different stationary fuel cell market segments, which are of high relevance for these stacks, i.e. micro-CHP in the range of 1 to 5 kW_{el}, industrial CHP between 20 and 500 kW_{el}, as well as off-grid power generation in the range of 100 W_{el} to 5 kW_{el}.

The following parameters were chosen for the technical readiness definition:

a) Volumetric power density in W/l; it scales proportionally to the amount of material used for the stack and the thermal insulation. It is also an indication for the long-term cost potential, but on the other hand, not a top priority for stationary products, as it would be the case e.g. for automotive applications.

b) Durability measured in a lab test or in the field by hours of continuous or combined operation demonstrated; the rationale behind this parameter is, that it defines the stack replacement cycles and thus the total cost of ownership (TCO) of the system. This parameter is related to stack design, manufacturing robustness and material effects.

c) Performance degradation rate, expressed by the growth rate of area specific resistance (ASR) in mΩ · cm² / 1.000 h; this parameter is the loss of power or efficiency of the stack and the system induced by material degradation. The parameter is more related to material than engineering issues, especially if long-term stable trends can be observed.

d) Combined cyclisation capability measured in system cycles from ambient to operation temperature; reasonable start/stop-cyclisation capability is required for most, especially smaller systems, and defines together with the degradation rate the lifetime of the stack. Combined cyclisation capability means here, that there is no protective gas on the anode side during start-up and shutdown, and therefore a certain RedOx impact will occur, affecting the Ni/NiO anode structure.

These parameters can be measured exactly in lab tests or during system operation. However, the test conditions (temperature, fuel composition, fuel utilization, details of cycling operation, etc.) and even the test-rig design will have significant impact on the results. Therefore, exact comparisons can be made only for those tests, which were executed in the same lab under carefully defined test conditions.

As mentioned before, the parameters described above were standardized to a percent scale p_i with 100 % representing the ideal or target value, which can be either low or high. For calculating the technical readiness tr, a weight factor or priority value q_i is applied, cf. Equation 1.

$$tr = 1 - \max[(1 - p_i) \cdot q_i] \tag{1}$$

Results of the TRL estimation for the CFY stack and the eneramic® stack are shown for different market segments in Table 2 and Table 3, respectively. It should be noticed that the technical readiness of stack technologies in each market segment is defined by individual target values for each market segment and a relative priority factor. In Table 3, the eneramic® stack is not evaluated for the market segment of industrial CHP, as the stack is too small to be reasonably integrated into such systems.

Table 2. Technical readiness of CFY stack technology in three different market segments.

Assessment Parameter			**Micro-CHP**			**Industrial CHP**			**Off-grid Power**		
	Unit, Description	*Status SOFC*	q_i	*Target*	*single TRL*	q_i	*Target*	*single TRL*	q_i	*Target*	*single TRL*
TRL demonstrated	cf. Table 1	-	1	-	60 %	1	-	50 %	0,5	-	80 %
Volumetric power density	W / l	400	0,75	250	100 %	0,5	250	100 %	0,7	350	100 %
Durability	kh	19	0,75	40	48 %	0,5	60	32 %	1	10	100 %
Degradation rate (ASR)	mΩ cm² kh^{-1}	17	1	10	59 %	1	10	59 %	1	20	100 %
Cyclisation capability	cycles	60	1	200	30 %	0,5	100	60 %	0,7	150	40 %
Total TRL					**30 %**			**50 %**			**58 %**

Table 3. Technical readiness of eneramic® stack technology in two different market segments.

Assessment Parameter			**Micro-CHP**			**Industrial CHP**			**Off-grid Power**		
	Unit, Description	*Status SOFC*	q_i	*Target*	*single TRL*	q_i	*Target*	*single TRL*	q_i	*Target*	*single TRL*
TRL demonstrated	cf. Table 1	-	1	-	50 %				0,5	-	80 %
Volumetric power density	W / l	364	0,75	250	100 %				0,7	350	100 %
Durability	kh	19	0,75	40	48 %				1	10	100 %
Degradation rate (ASR)	mΩ cm^2 kh^{-1}	17	1	10	59 %				1	20	100 %
Cyclisation capability	cycles	100	1	200	50 %				0,7	150	67 %
Total TRL					**50 %**			**n/a**			**77 %**

The production readiness of CFY stack and eneramic® stacks as shown in Table 4 and Table 5 was again calculated according to Equation 1. Here, the only quantitative parameter is the actual production volume versus the target production volume in each market segment. The target value of the annual production volume is the cumulated power generation capacity of produced stacks, where a viable business case could be established and estimated target cost are achieved. The target production volumes identified by separate evaluation is 2 MW for micro-CHP, 20 MW for industrial CHP and 200 kW for the off- grid case. The eneramic® stack production is still on a very low level with respect to volume, which results in a low TRL for manufacturing. The principle assessment logic still works sufficient with the remaining qualitative parameters; however, subjective judgement is more dominant, here.

Table 4. Manufacturing readiness of CFY stack technology in three different market segments.

Assessment Parameter		**Micro-CHP**		**Industrial CHP**		**Off-grid Power**	
	Target	q_i	*single TRL*	q_i	*single TRL*	q_i	*single TRL*
Required manufacturing capacity	see right		2 MW p.a.		20 MW p.a.		200 kW p.a.
Annual production volume	100 % p.a.	1	15 %	1	2 %	1	100 %
Technology for volume production	proven	0,75	50 %	0,75	25 %	0,75	100 %
In-line quality inspection	proven	0,5	50 %	0,5	50 %	0,5	50 %
Equipment / plants for target volume	available	0,5	50 %	0,5	25 %	0,5	100 %
Competitive supply chain	established	1	90 %	1	90 %	1	90 %
Total TRL			**15 %**		**2 %**		**75 %**

Table 5. Manufacturing readiness of eneramic® stack technology in two different market segments.

Assessment Parameter		**Micro-CHP**		**Industrial CHP**		**Off-grid Power**	
	Target	q_i	*single TRL*	q_i	*single TRL*	q_i	*single TRL*
Required manufacturing capacity	see right		2 MW p.a.				200 kW p.a.
Annual production volume	100 % p.a.	1	1 %			1	8 %
Technology for volume production	proven	0,75	50 %			0,75	50 %
In-line quality inspection	proven	0,5	80 %			0,5	80 %
Equipment / plants for target volume	available	0,5	20 %			0,5	50 %
Competitive supply chain	established	1	100 %			1	100 %
Total TRL			**1 %**		**n/a**		**8 %**

The off-grid segment case in Table 4 demonstrates the effect of the priority or weight factor in the TRL calculation. Total TRL for manufacturing in this segment is 75 %, not 50 %, as the parameter for in-line quality inspection is prioritized with 50 %, only.

However, quality control including appropriate in-line inspection technologies is an especially important factor. A SOFC stack is a serial assembly of 15 to 60 thin ceramic sheets with printed electrodes, called membrane electrode assembly (MEA) or SOFC single cell. A single cell failure will result in a failed stack, something that can be detected only after final stack joining at the end of stack manufacturing. Without appropriate quality inspection technologies and stable processes, an acceptable yield rate in stack production is not achievable. Fraunhofer IKTS is therefore developing sophisticated quality inspection technologies for series production of component parts and complete SOFC stacks.

A third field considered for successful market deployment of SOFC technology is the business environment for the commercialization. Here, the evaluation is made from a German or European perspective. The missing coverage of fuel cell micro-CHP products in eco-design and energy labeling directives of the European Union is one aspect considered here. For Asian or American countries, potential results in this segment might by different.

The chosen assessment parameters include required legislation and public perception as well as target cost for the target volumes in different segments, considering the design and technology available today. Results are summarized in Table 6 and Table 7 below.

Table 6. Business readiness of CFY stack technology in three different market segments.

Assessment Parameter	Micro-CHP		Industrial CHP		Off-grid Power	
	q_i	*single TRL*	q_i	*single TRL*	q_i	*single TRL*
Legislation as required	0,75	80 %	1	90 %	1	100 %
Positive public perception / acceptance	0,5	100 %	0,5	100 %	0,3	100 %
Viable business models at target cost	1	100 %	1	90 %	1	90 %
*Stack target cost at target vol. for business case**	1	100 %	1	43 %	0,9	57 %
Total TRL		**85 %**		**43 %**		**61 %**

**) in market segment micro-CHP: 4.000 €/kW$_{el}$ @ 2 MW$_{el}$ p.a.*

Table 7. Business readiness of eneramic® stack technology in two different market segments.

Assessment Parameter	Micro-CHP		Industrial CHP		Off-grid Power	
	q_i	*single TRL*	q_i	*single TRL*	q_i	*single TRL*
Legislation as required	1	80 %			1	100 %
Positive public perception / acceptance	0,75	100 %			0,3	100 %
Viable business models at target cost	1	100 %			1	90 %
*Stack target cost at target vol. for business case**	1	100 %			1	88 %
Total TRL		**80 %**		**n/a**		**88 %**

**) in market segment micro-CHP: 4.000 €/kW$_{el}$ @ 2 MW$_{el}$ p.a.*

By calculating the mean values of the three TRL results representing technical maturity, manufacturing technology and business case viability, the overall technology readiness of the specific SOFC stack in a specific stationary market segment were evaluated. Results are shown in Table 8 below.

Table 8. Overall technology readiness of CFY stack technology and eneramic® stack technology in three different market segments.

	Priority	Micro-CHP 1 .. 5 kW_{el}	Industrial CHP 5 .. 100 kW_{el}	Off-grid Power 0,1 .. 1 kW_{el}
CFY stack technology				
Technical maturity	100 %	30 %	50 %	58 %
Manufacturing technology	80 %	15 %	2 %	75 %
Buisness case viability	70 %	85 %	43 %	61 %
Total TRL		**51 %**	**44 %**	**70 %**
eneramic® stack technology				
Technical maturity	100 %	50 %		77 %
Manufacturing technology	80 %	1 %		8 %
Buisness case viability	70 %	80 %		88 %
Total TRL		**52 %**	**n/a**	**65 %**

Based on the results in Table 8 it can be concluded that the summary figure might be less important than the specific results in different sub-fields. The extremely low readiness of eneramic® stack in manufacturing aspects is attributed to low production volumes and should be drastically improved in rather short term if required investment in production equipment can be realized.

RESULTS AND ANALYSIS

Technical readiness data for the off-grid market segments are the highest values as lifetime and degradation target values are lower in this segment. Results can also be visualized in radar diagrams as shown in Figure 3 and Figure 4.

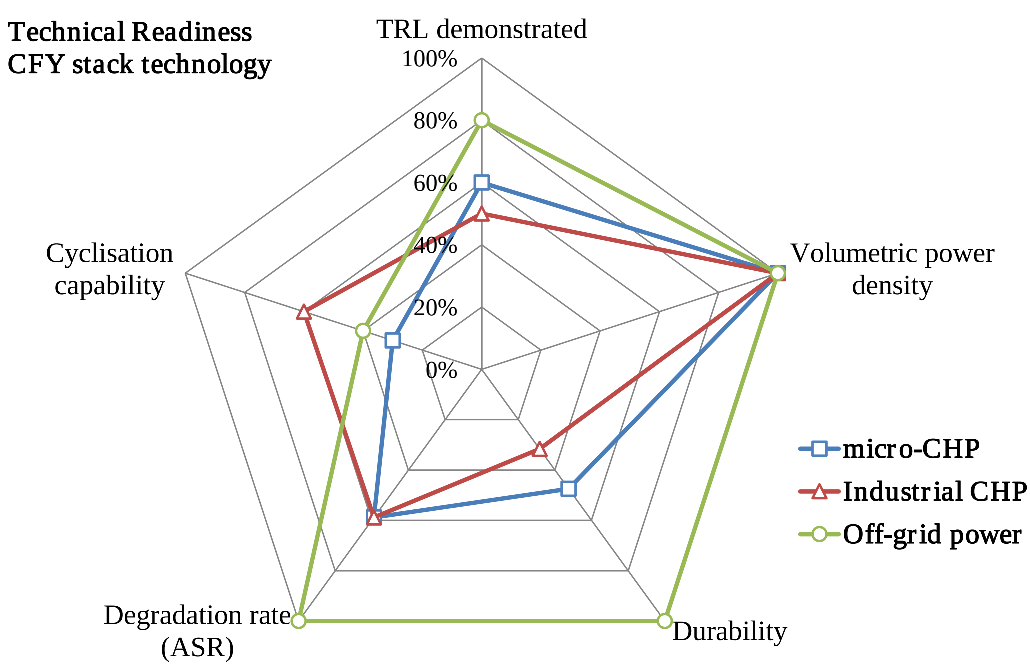

Figure 3. Visualization of technical readiness for CFY stacks in three different market segments.

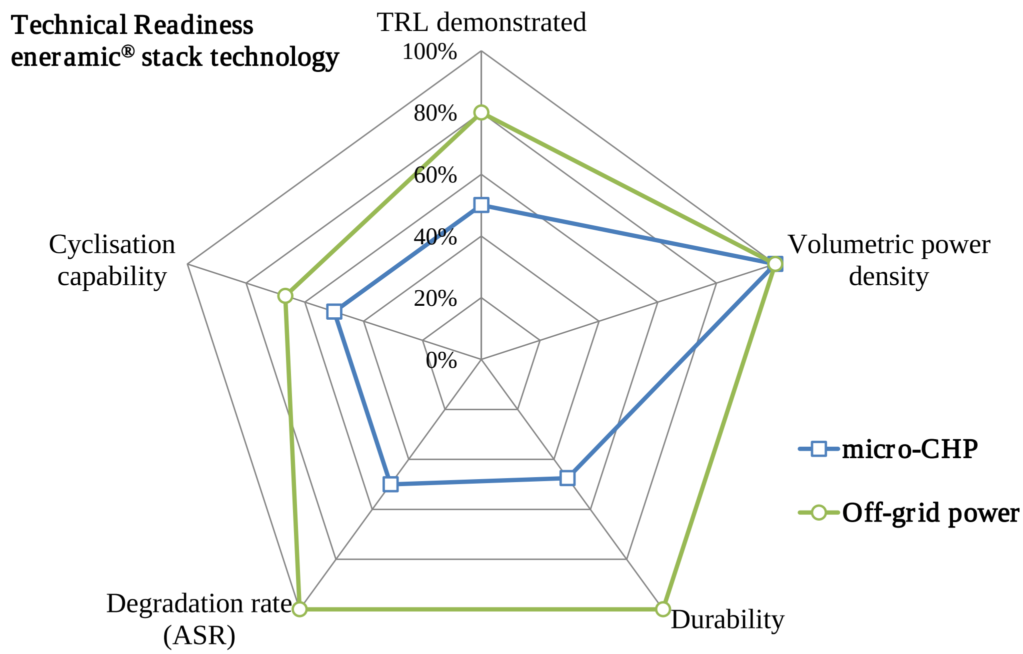

Figure 4. Visualization of technical readiness for eneramic® stacks in two market segments.

The comparison between the three considered market segments underlines that technical readiness of a particular stack technology might be significantly varying for different markets segments. For this reason and following the overall TRL results according to Table 8, Fraunhofer IKTS believes that a commercialization should start in the off-grid market segments. The recent initial market success of German company NewEnerday GmbH and successful field trials with the eneramic® system developed by IKTS underline this strategy.

The TRL analysis work can, however, reveal additional data of interest. Figure 5 shows how the technical readiness of the eneramic® stack technology platform has evolved over the last three years.

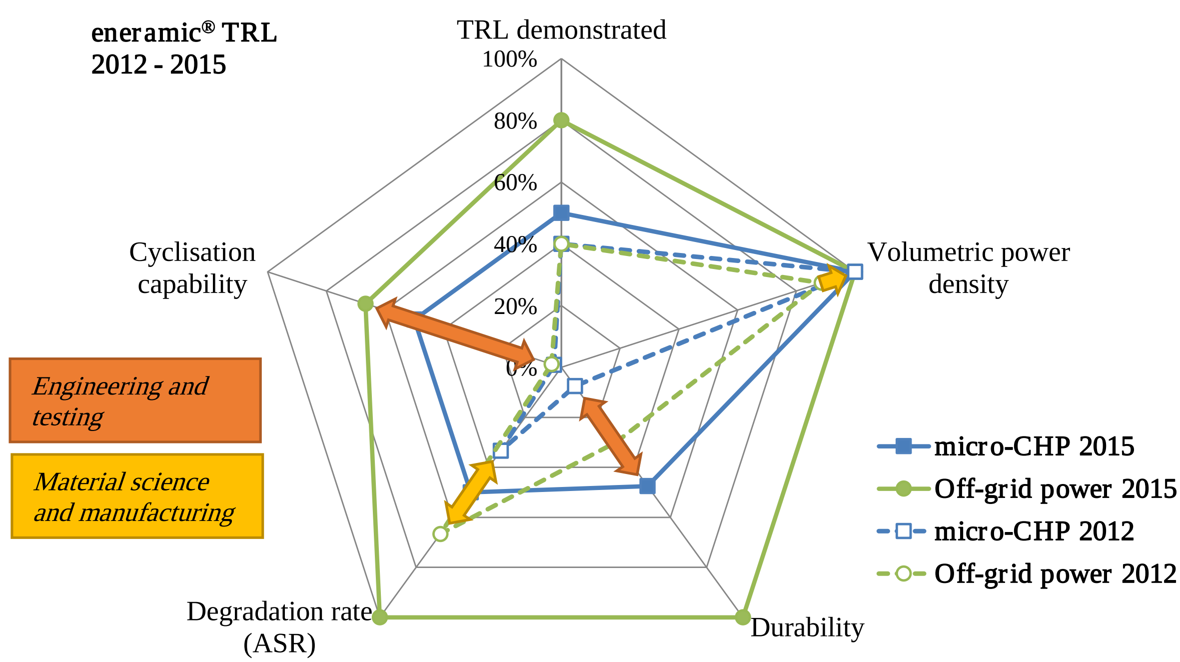

Figure 5. TRL evolution of the eneramic® stack technology platform over three years, 2012 – 2015.

Significant progress had been achieved in any of the considered parameters. This is a result of intensive testing and efficient engineering work. Relative progress however is less, where not engineering work but advances in material science are required to get substantial progress. This principle observation was to be seen even more clearly with other stack technologies not published here. R&D and business teams should focus in the early development phase on parameters like degradation rates or power densities for getting them right for their business case. Otherwise, there is a significant risk of failure.

CONCLUSIONS

Technology Readiness (self) evaluation is becoming an important element in Horizon2020 research program of the European Union and other similar programs. While this TRL definition helps to identify the relative maturity of a particular technology and to compare different technologies, it gives no information how far away from commercialization a technology really is.
In this paper, a more detailed analysis and comparison is proposed. The technology readiness calculated by the suggested method is always specific for a given solution and a targeted market segment or application.

The detailed technology readiness review has been applied to SOFC stacks, the heart of any SOFC system. The analysis published here is specific to the three stationary market segments micro-CHP, industrial CHP and off-grid power generation, and is made for the planar SOFC stacks developed at Fraunhofer IKTS.

The analysis makes clear, that if fundamental technical parameters, which are primarily driven by progress in material development, are not on the level required for commercialization yet, a near term commercialization is rather uncertain. This is true, even if a formal TRL level of 8 (tested successfully in the field) can be claimed with some evidence. A clear evaluation of SOFC technology readiness and a market segment specific gap analysis highlighting R&D needs is given above. The methodology can be easily applied to other stacks, if required test results and market data are available. Ideally, testing should be done in one lab.

Based on this analysis, the off-grid market segment offers best and short-term market opportunities for the SOFC technology. This market segment accepts highest cost, which can be reached with lower production volumes, and has at least in some applications lower lifetime and durability requirements, which are met by IKTS stacks today, already.

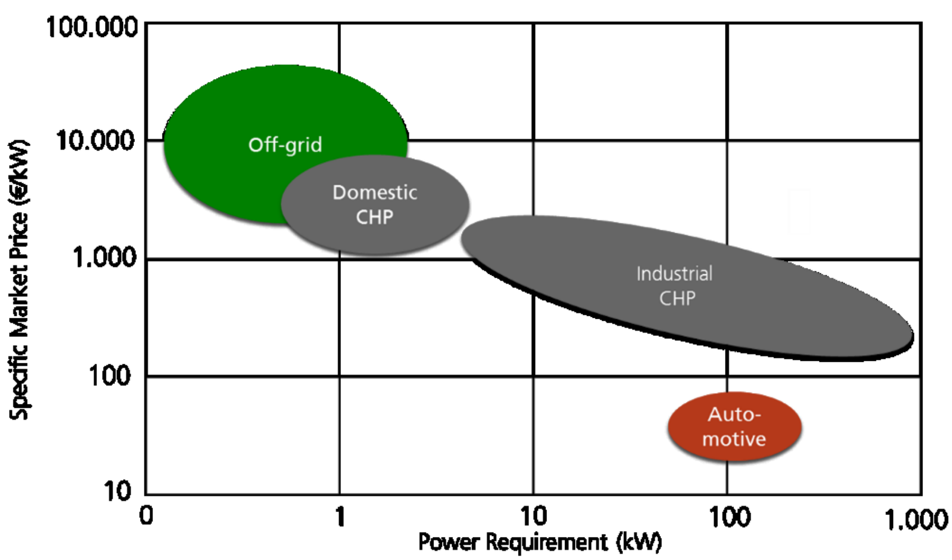

Figure 6. Specific market prices in different market segments for SOFC systems.

The analysis also reveals why the business case of a company, which is basically manufacturing stacks for different market segments, can be viable. A successful business in the off-grid market will help this company to gather learning experiences with lower volumes in a market that accepts significant higher prices while establishing volume and robust manufacturing for other even bigger market segments. The required specific cost level given in Figure 6 is one key indicator for the attractiveness of the off-grid market.

The herein presented analysis is made for SOFC stacks developed at Fraunhofer IKTS. However, our insight into other stack technologies and the general impression from many presentations in the numerous conferences lead to the impression that relative technology readiness of stacks at IKTS is at rather high level and that especially durability and performance degradation is in many other cases not in the target window for a successful commercialization.

There is one exception, however: Japanese SOFC stacks are outstanding with regard to reported lifetime and degradation rates. It should be noted that the early focus on the durability testing and analysis of failures at AIST by looking at different stacks from different manufacturers is one of the success factors of Japanese fuel cell industry. The project "Development of System and Elemental Technology on SOFCs" (2008-2012), sponsored by New Energy Development Organization (NEDO), included the important sub-task: "Fundamental Research for Improvement of Durability"[6]. Current market prices for Japanese SOFC system indicate however, that these systems and stacks are still too expensive as the sales price in 2015 is above 20.000 US$ for a system rated at 700 W_{el}, even while more than 10.000 systems have been sold (which is equivalent to a production volume of about 3 to 5 MW_{el} per year). It becomes obvious, that the target value of 4.000 €/kW_{el} at a production rate of 10 MW_{el} per year is not reached, yet.

The principle of technology readiness evaluation can be transferred easily to other technologies. In any case, a detailed understanding of the technology including internal testing facilities is required to do so.

ACKNOWLEDGEMENTS

Part of this research work has been funded by the Free State of Saxony and the European Union under contract 100116909. This funding is highly appreciated.

This work has been developed in long discussions with my colleagues at Sunfire GmbH and Fraunhofer IKTS. Most of the technical input is based on their test results and findings. Their careful work over the last ten years is the fundament of this summary paper.

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