Clean Energy, 2020, 1–10

doi: 10.1093/ce/zkaa015
Advance Access Publication Date: 2 November 2020
Homepage: https://academic.oup.com/ce

ENGINEERING PRACTICE

Facilitating Water electrolysers for electricity-grid services in Europe through establishing standardized testing protocols

Shi You[1,*], Regine Reissner[2], Christoph Imboden[3], Cyril Bourasseau[4], Pablo Marcuello[5], Daniel Greenhalgh[6], Ben Green[6], Laura Abadía[7], Vanesa Gil[7], Marius Bornstein[8], Yi Zong[1], Xu Chen[1] and Chresten Træholt[1]

[1]Department of Electrical Engineering, Technical University of Denmark, Elektrovej 325, DK-2800 Kgs. Lyngby, Denmark
[2]German Aerospace Center, Institute of Engineering Thermodynamics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany
[3]Lucerne School of Engineering and Architecture, Technikumstrasse 21, CH-6048 Horw, Switzerland
[4]CEA, Liten, Department of Biomass and Hydrogen Technologies, 17 Avenue des Martyrs, 38000 Grenoble, France
[5]Industrie Haute Technologie, Clos-Donroux, C. P. 228, 1870 Monthey 1, Switzerland
[6]ITM Power, Altas way 22, Sheffield, S4 7QQ, UK
[7]Foundation for the Development of New Hydrogen Technologies in Aragon, Ctra. N-330a, km. 56622197 Huesca, Spain
[8]NEL, Department of Hydrogen Electrolyser, P.O. Box 24, NO-3671 Notodden, Norway

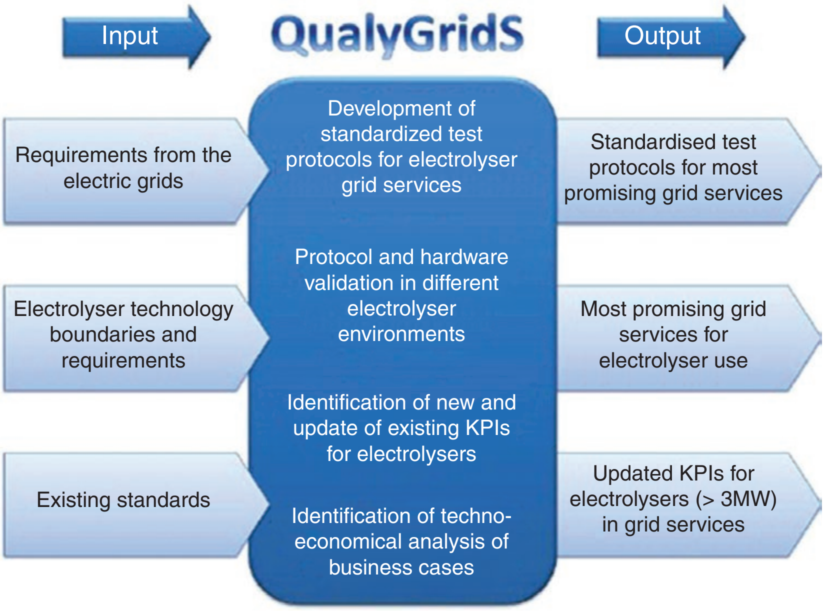
*Corresponding author. E-mail: sy@elektro.dtu.dk

Abstract

Electrolysers, which convert electricity into hydrogen, have the potential to offer a variety of electrical-grid services, therefore facilitating the integration of intermittent renewables into electrical grids. Among various activities that aim to unlock this hidden value, the 3-year European Union project QualyGridS launched in 2017 aims to establish standardized testing protocols for electrolysers to perform electricity-grid services. This paper shares experience and intermediate results of QualyGridS with respect to the testing protocols, test benches and testing results. The results of this work facilitate mutual understanding between the electricity industry and the hydrogen industry, support further development of the cross-sector testing standards, guide the design and selection of grid-service-oriented electrolyser applications and foster the transition towards a fossil-free-energy future based on high shares of hydrogen and other renewable solutions.

Received: 14 May 2020; **Accepted:** 7 August 2020

Graphical Abstract



Keywords: electrolyser; hydrogen; electrical-grid service; QualyGridS; test bench; testing protocols

Introduction

The European Union has a target to cut its greenhouse-gas emissions by 80–95% below 1990 levels by 2050 to address global warming. In the electricity sector, the integration of significant amounts of intermittent renewable energy sources like wind and solar power is currently the most commonly used measure for countries in Europe to achieve the 2050 goal [1]. Consequently, the immediate need for identifying and enabling new types of flexible and green resources to provide electrical-grid services is clear due to the intermittent natures of wind and solar energy [2, 3]. Many examples of the new types of flexible resources can be found in non-electricity sectors like gas [4], heat [5] and transport [6], where electrification strategies are designed, developed and implemented in order to create positive synergic effects, e.g. using excessive green renewables for replacing direct fossil-fuel use [7].

An electrolyser converts electricity into hydrogen. Today, electrolysers constitute ~5% of global hydrogen production [8]. The produced hydrogen is used in a variety of applications such as fuel-cell vehicles, green gas, re-electrification and industrial use. The potential for using hydrogen in multisectoral applications, also known as hydrogen-to-X (HtX), has triggered a growing interest in different electrolyser technologies and HtX applications [9, 10] as well as a number of bankable business cases [11]. Recent analyses have also shown that there is a promising market potential for electrolysers beyond 2025 [12].

Although electrolysers are currently little involved in offering grid services, this potential has been widely studied [13–16] and initially demonstrated by several pilot projects in Europe [17–19], driven by the increasing needs and value of flexibility resources. The flexibility potential of an electrolyser resides in its electrical-power consumption when it is regulated via incentives or direct control signals. Depending on its application and on the associated design principle of an electrolyser, the corresponding flexibility potential can vary in terms of power capacity, rate of change, response time, service duration and location, etc. When an electrolyser application includes a storage option, such as a hydrogen tank or a natural-gas grid, the overall flexibility potential will be greatly enhanced.

The QualyGridS project (2017–2020), with 10 research and industrial partners (including three electrolyser-technology suppliers, one standardization institute, five research organizations and the European Fuel Cell Forum) from Europe, aims to establish standardized testing protocols for electrolysers to perform electrical-grid services through a series of structured studies as in Fig. 1 [20]. The draft protocols developed were applied to both alkaline and proton-exchange membrane (PEM) electrolyser systems that are off-the-shelf technologies. Additionally, a techno-economic analysis of business cases was performed to identify the most promising business cases for MW-scale electrolysers in Europe, taking into account the corresponding conditions of the electrical grid and the energy market. Through a close collaboration with European and international standardization organizations, the developed draft protocols are being prepared for a standardization process. Part of the testing protocols and economic analysis also includes updating existing and defining new Key Performance Indicators for grid-service-oriented electrolysers, therefore offering clear guidance for future development and electrolyser applications.

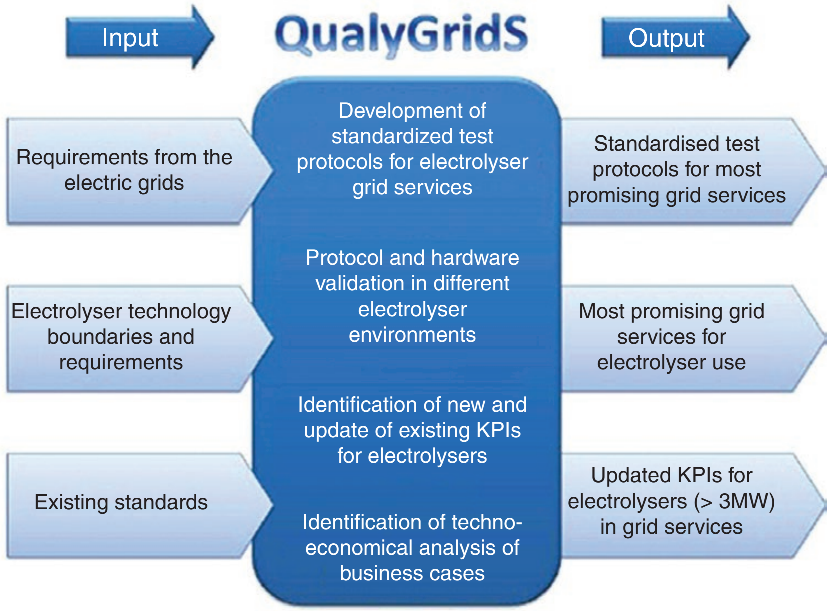


Fig. 1: Concept of QualyGridS Reproduced with permission from DLR.

This paper presents the technical achievement of QualyGridS with respect to the draft testing protocols, test benches and selected testing results. The protocols were developed according to technical requirements that are adopted by a majority of electricity-grid operators in Europe for grid-service qualification. To test and validate the developed protocols, five test benches with different electrolysers set-ups (ranging from 10 to 300 kW) were developed and applied in Denmark, Germany, Spain, Switzerland and Norway, respectively. The collected testing results show that the electrolyser systems are, in principle, able to fulfil the requirements of grid services if certain improvements can be implemented, such as replacing current control with power control.

Such knowledge and experience can bring relevant stakeholders and society multifold benefits, e.g. facilitating mutual understanding between the electricity industry and the hydrogen industry, supporting further improvement of the developed testing protocols, guiding the design and selection of relevant techno-economic case studies and business models and fostering a transition towards fossil-free energy systems.

1 Testing protocols for electrolysers to perform electricity-grid services

1.1 Electricity-grid services, technical requirements and pre-qualification

In Europe, transmission system operators (TSOs) and distribution system operators (DSOs) are obliged for maintaining a safe and reliable power transfer for different network levels. To fulfil this, there exists a variety of grid services, as depicted in Fig. 2. These services are often integrated into the planning, operation and management functions of the grid operators [21]. The grid operators can either purchase these services through various marketplaces or oblige certain units to provide these services.

At the transmission level, many of these services are referred to as ‘ancillary services’ and can be acquired by the TSO from an ancillary-service provider through an ancillary-service market or a balancing market. Classical types of ancillary services include frequency response, voltage control, and capacity and congestion management, redundancy support, etc. These services are used to meet various power- and energy-balancing requirements in a power system. Fig. 3 depicts a standard description of balancing products, which is recommended by ENTSO-E [22]. Accordingly, requirements for various grid services could be specified in a harmonized way.

Before the service provider enters the market, it is a prerequisite to pass a pre-qualification test through which the grid operator can assess the service provider’s ability against the technical requirements of the targeted service. The duration of a pre-qualification test can vary from short (i.e. a few minutes) to medium (i.e. up to 2 hours) to long (i.e. up to weeks). The short-duration tests are normally made to examine one or more individual technical aspects. The medium and long tests are conducted to test sustainability. Fig. 4 presents an example of a pre-qualification random test for Frequency Containment Reserve (FCR) in Denmark [23]. This automatically activated grid service requires both the activation and the deactivation periods to be <30 seconds, a delivery period of >15 minutes and power deviations within a permissible range during the period of ramping.

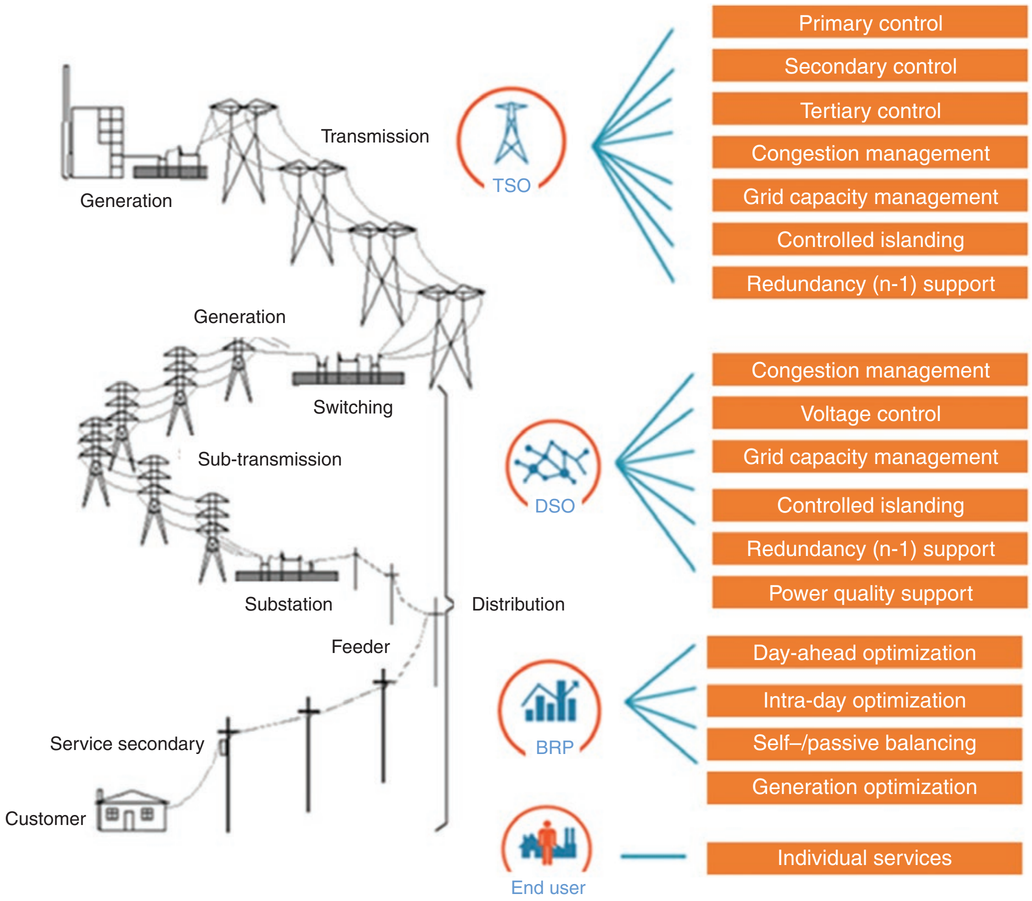


Fig. 2: A schematic overview of services requested by grid operators and other stakeholders in a contemporary power system

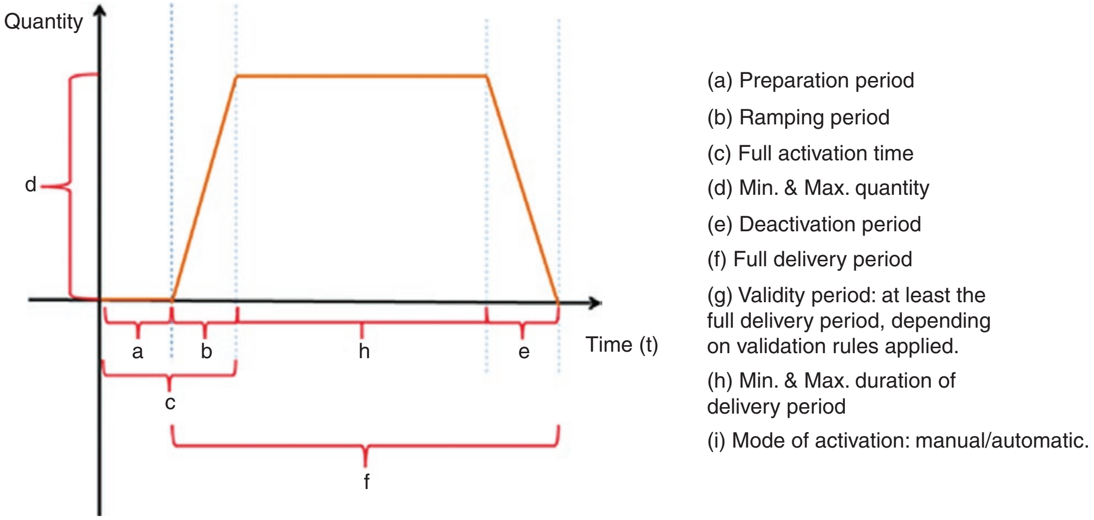


Fig. 3: Standard description of any balancing product with variable characteristics (a)–(i), recommended by ENTSO-E

The technical characteristics and qualification requirements for grid services requested by the DSOs are more or less the same as those for the TSOs. Acquisitions of the DSOs' grid services are normally managed through bilateral contracts. In practice, the grid services are applied to address techno-economic issues of an individual power system. Therefore, the requirements even for the same type of grid services can be different from one grid operator to another. Regarding different aspects of grid services, technical requirements and pre-qualification standards, the technical report 'Grid service catalogue for water electrolysers' [24] published by the QualyGridS consortium presents a detailed overview of grid services applied by the grid operators in Europe.

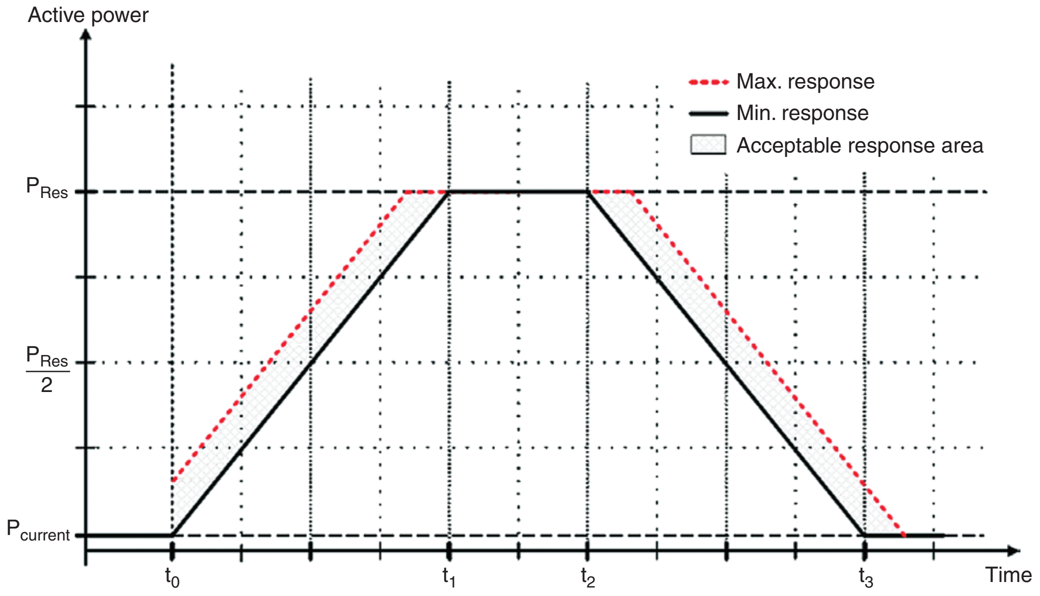


Fig. 4: A random FCR-response qualification test specified by Danish TSO Energinet

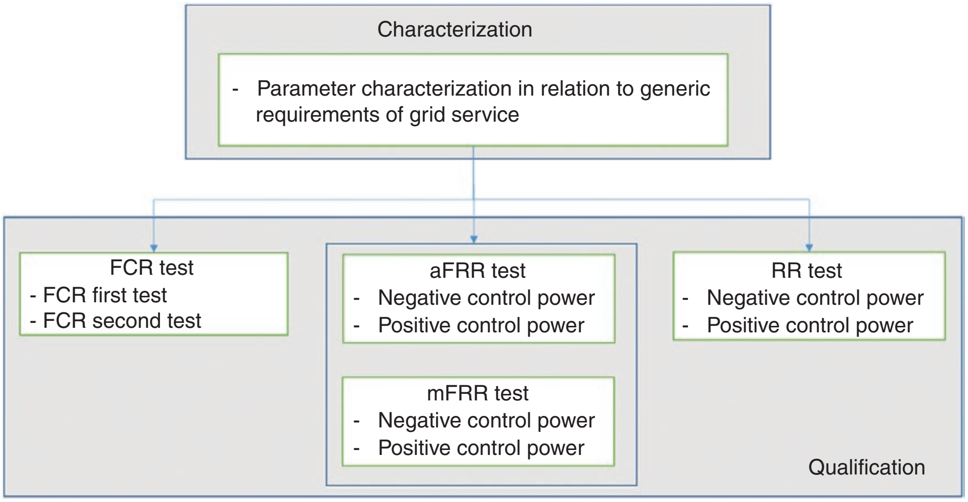


Fig. 5: A schematic overview of the draft testing protocols

1.2 Testing protocols in draft

Based on a comprehensive review and survey of grid-service requirements implemented by grid operators from Denmark, France, Germany, the Netherlands, Norway, Spain, Switzerland and the UK, the QualyGridS draft testing protocols are developed as a set of test protocols. Existing standards, such as INTERNATIONAL STANDARD ISO 22734-1 ‘Hydrogen generators using water electrolysis process’, are also used as normative references during the process of protocol development. As illustrated by Fig. 5, the draft testing protocols contain mainly two parts, i.e. characterization and qualification.

The characterization part aims to determine the basic characteristics (e.g. start-up time, power range of operation and ramping ability during power variation) of a tested electrolyser system in order to find out for which grid services the electrolyser might in principle be suitable. The qualification part includes a set of qualification tests, targeting three balancing services, namely FCR, automatic/manual frequency restoration reserve (aFRR/mFRR) and replacement reserve (RR). The three balancing services are widely used by grid operators in Europe to cope with power-balancing issues at varying time scales and capacity levels. For instance, the full activation time for FCR is often <30 seconds, for FRR is between 30 seconds and 15 minutes, and for RR is >15 minutes. As detailed technical requirements and pre-qualification standards for the same type of grid service can differ from one grid operator to another, each qualification test protocol is developed by uniting similar pre-qualification tests published by different grid operators (i.e. for the same type of grid service but with different requirements) into one test [25]. This comprehensive approach ensures a high reliability and generality of the developed first-draft standardized testing protocols. Further, the developed protocols can be tailored to target a specific region/country/grid operator if relevant.

2 Application of the testing protocols

2.1 An overview of the QualyGridS test benches

In the QualyGridS projects, five electrolyser test benches were implemented by Technical University of Denmark (DTU) from Denmark, Deutsches Zentrum für Luft- und Raumfahrt (DLR) from Germany, New NEL Hydrogen AS (NEL) from Norway, Industrie Haute Technologie (IHT) from Switzerland and Fundación para el Desarrollo de las nuevas tecnologías del Hidrógeno en Aragón (FHA) from Spain, respectively. A graphical view of the test benches is given in Fig. 6. The five test benches include both PEM and alkaline electrolysers produced by different manufacturers, ranging from 10 to 300 kW. Each electrolyser system is powered by the AC grid through an AC/DC rectifier, wherein power-metering solutions are applied to monitor the AC and DC electric-power features of the electrolyser system and its key components, such as stacks and the Balance of Plant (BoP) at a resolution of ≥5 seconds. All electrolysers are current-controlled, implying that active-power control of the electrolysers can only be indirectly implemented by regulating the DC-current set-points. Other feature-testing options related to performance and durability for the stacks are also viable, but are considered

Fig. 6: QualyGridS test benches implemented at (a) DTU, (b) DLR, (c) FHA and (d) NEL

Table 1: Basic electrical parameters of QualyGridS test benches

	DTU	DLR	FHA	IHT	NEL
Nominal power of the tested electrolysers (kW)	28	50	10	50	300
Electrolyser type	PEM	PEM	Alkaline	Alkaline	Alkaline
BoP power (kW)	<1	<4	3.3	<1	2–3
Supply voltage	3 × 400 V 50 Hz	3 × 400 V 50 Hz	3 × 400 V 50 Hz	3 × 400 V 50 Hz	3 × 400 V 50 Hz
DC-stack voltage (V)	0–13	0–17	0–18	0–18	0–250
DC-stack current (A)	0–3000	0–3000	0–3500	0–10 000	0–1600

to be out of the project's scope. Table 1 gives a brief overview of the electrical parameters of the five test benches.

In order to match the requirements of grid-service-qualification tests, each test bench was implemented with state-of-the-art industrial measurement and data-logging solutions. For example, the grid side measurement at DTU's test bench was taken care of by a 'Network Manager' solution from ABB, which is a commercial supervisory control and data-acquisition system. The solution is widely adopted in the power sector for power automation, control and energy management, etc. At DTU, this grid interface is used for testing the grid integration of various electrical-component technologies like wind turbines, solar panels and batteries, etc. Within such a set-up, the real-time grid data could be measured by highly accurate remote terminal units (RTUs), i.e. the accuracy of the voltage and current is 0.2% true RMS, the accuracy of power and energy is 0.5% for four-quadrant metering, etc.; therefore, it matches fully the requirements for a grid-service test bed. From the electrolyser side, standard Siemens PLCs are used to control and log the electrolyser's operational performance. Combining an advanced grid-service test bed with off-the-shelf electrolyser systems to a large degree resembles how the electrolysers will be tested by the grid operators if they would like to provide the grid services via today's electricity marketplace.

Table 2: Description of protocol for the determination of the start-up time from standby mode

Step	Description
1	Set the power of the system power control to nominal power
2	Wait for rectifier input power constant by ±5% in a 15-minute interval

2.2 Selected test protocols and test results

In this section, two draft test protocols and the intermediate results are selected for presentation.

2.2.1 Protocol for determination of start-up time from standby mode

The protocol 'Determination of start-up time from standby mode' is given in Table 2, as one example of the protocols related to system-parameter characterization. The draft protocol, as described in its name, aims to characterize the start-up time from the standby mode to the electrolyser's nominal power.

Fig. 7a and b presents the test results measured in per-unit values for the rectifier output of and grid-power input to the electrolyser system, respectively. When the power consumption of the electrolyser is regulated to reach its nominal value, it takes ~1 second for the rectifier output to reach its nominal value and stay within a ±5% permissible range afterwards. However, when the corresponding dynamics are measured from the grid side, it takes ~200 seconds for the electrolyser to ramp from its standby load to nominal load.

2.2.2 Protocol for aFRR/Positive Control Power/Downward medium and fast ramp protocol from upper power level

The test protocol 'aFRR/Positive Control Power/Downward medium and fast ramp protocol from upper power level' is presented as another example. The draft protocol aims to test an electrolyser's ability against the grid-service requests of dynamic-load reductions. The protocol has 38 steps as described in Table 3 and requires pre-determination of the operation range between P_{up} and P_{low}. It takes ~4.5 hours to finish the test by implementing a load profile as illustrated in Fig. 8.

The protocol also defines the following qualification criteria that are commonly adopted by the grid operators:

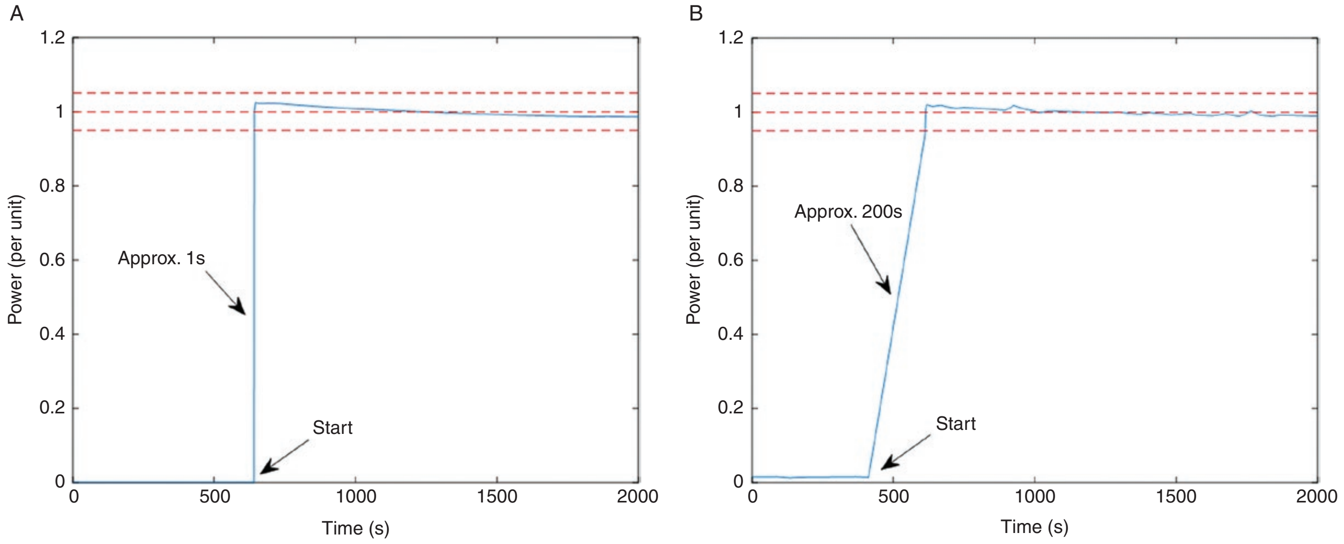


Fig. 7: Testing results of start-up time from standby mode measured for a PEM electrolyser with (a) rectifier output in DC power and (b) grid-power input to the entire system (including BoP)

Table 3: Description of test protocol aFRR/Positive Control Power/Downward medium and fast ramp protocol from upper power level

Step	Description
1	Set system at P_{up}
2	Wait for system power to stabilize
3	At $t = t_1$, initiate power ramp of power (–25% (P_{up}–P_{low})) in 133 seconds
4	$t = t_1$ + 133 seconds: end of the ramp
5	Keep set power for 5 minutes
6	Set system at P_{up}
7	Wait for system power to stabilize
8	At $t = t_2$, initiate power ramp of power (–50% (P_{up}–P_{low})) in 133 seconds
9	$t = t_2$ + 133 seconds: end of the ramp
10	Keep set power for 5 minutes
11	Set system at P_{up}
12	Wait for system power to stabilize
13	At $t = t_3$, initiate power ramp of power (–75% (P_{up}–P_{low})) in 133 seconds
14	$t = t_3$ + 133 seconds: end of the ramp
15	Keep set power for 5 minutes
16	Set system at P_{up}
17	Wait for system power to stabilize
18	At $t = t_4$, initiate power ramp of power (–100% (P_{up}–P_{low})) in 300 seconds
19	$t = t_4$ + 300 seconds: end of the ramp
20	Keep set power for 15 minutes
21	At $t = t_5$, initiate power ramp of power (+100% (P_{up}–P_{low})) in 300 seconds
22	$t = t_5$ + 300 seconds: end of the ramp
23	Keep set power for 15 minutes
24	At $t = t_6$, initiate power ramp of power (–100% (P_{up}–P_{low})) in 300 seconds
25	$t = t_6$ + 300 seconds: end of the ramp
26	Keep set power for 15 minutes
27	At $t = t_7$, initiate power ramp of power (+100% (P_{up}–P_{low})) in 300 seconds
28	$t = t_7$ + 300 seconds: end of the ramp
29	Wait for system power to stabilize
30	At $t = t_8$, initiate power ramp of power (–100% (P_{up}–P_{low})) in 30 seconds
31	$t = t_8$ + 30 seconds: end of the ramp
32	Keep set power for 15 minutes
33	Set system at P_{up}
34	Wait for system power to stabilize
35	At $t = t_9$, initiate power ramp of power (–100% (P_{up}–P_{low})) in 4 seconds
36	$t = t_9$ + 4 seconds: end of the ramp
37	Keep set power for 15 minutes
38	End of test

(i) The power change for each ramp must correspond to the target.

(ii) During the periods of constant-power request, the real system power must be in the range ±5% (P_{up}–P_{low}) around the requested power.

(iii) The actual power of the system must remain for 95% of the time within a permissible range, i.e. ±2.5% (P_{up}–P_{low}) around the requested ramping power.

The standard test profile of the protocol is illustrated in Fig. 8a, which provides a visual guide to facilitate the implementation. Measured results for one of the tested alkaline electrolysers are show in Fig. 8b, wherein the rectifier input AC power (excluding BoP) is measured. In Fig. 8b, the blue line indicates the set power with a range between the nominal load and 12% of the nominal load; the red line gives the difference between the measured real power and the set power. As indicated by the results, the alkaline electrolyser was able to follow well the power reference within the permissible-error range during constant-power periods; however, there are large errors during the ramp periods. This is primarily due to two reasons. First, the ramp period of the real power input could be longer than the ramp period defined by the protocol. Taking the largest deviation (i.e. the one equal to ~0.9 p.u.) as an example, the protocol at stage 33 sets system to P_{up}; however, it took ~30 seconds for the system to reach P_{up} from P_{low}. Second, the controller implemented is designed for DC-current following instead of active-power following, which also introduces a certain time delay. A classical PID (proportional–integral–derivative) controller implemented for power following should be able to address this issue properly.

In practice, the grid-service-qualification test is often an one-off test done by the grid operator. Therefore, the impact of performance uncertainties is already considered by the assessment criteria, e.g. 'the actual power of the system must remain for 95% of the time within a permissible range', as stated in the test protocol example. For characterization tests, repeated tests might be necessary if there is a demand for accurate parameter characterization. For instance, the start-up-time-determination tests may need to be done several times in order to get a range or an average value of the start-up time.

3 Conclusion and recommendation

The potential for using the flexibility of electrolysers for grid services is widely acknowledged. To fully unlock this potential, the QualyGridS project worked on establishing a set of standardized test protocols for electrolysers to perform electricity-grid services in Europe. Draft protocols were developed based on grid-service requirements and pre-qualification standards that are used by the grid operators in Europe, while five benches were used to validate the protocols by applying them to test electrolysers that are available in today's market.

Results achieved so far have demonstrated the practicality of the developed protocols and have also shown that there are multiple factors that could influence the qualification of an electrolyser for grid services, such as electrolyser technologies and system design, the selected range of load variation, configuration issues related to the inclusion

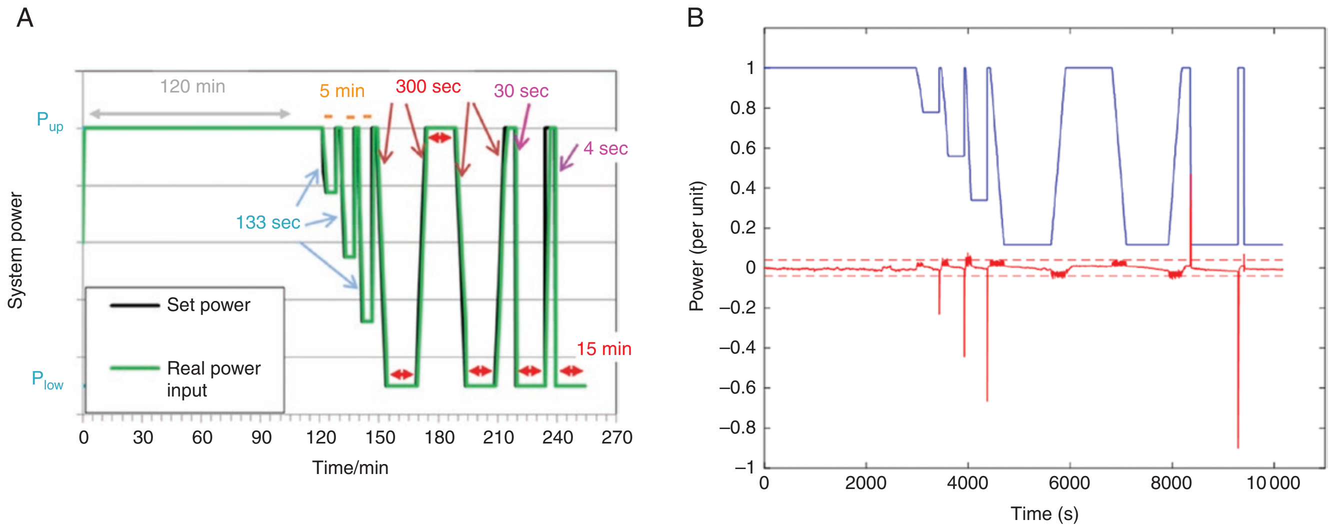


Fig. 8: Standard test protocol of aFRR/Positive Control Power/Downward medium and fast ramp protocol from upper power level with (a) reference profile and (b) the test results.

of BoP or not, delays caused by communication and other limitations of test benches, etc. Other issues such as a variation in the stack impedance during constant-load periods and the capability of the rectifier technologies applied can also influence the power-performance stability of the electrolyser. What has been particularly observed during the test is that, although power regulation of the electrolyser load can be achieved by changing the electrolyser DC-current set-points in real time, it is challenging to achieve highly accurate active-power control due to the variation in stack impedance. It is therefore highly recommended to use a dedicated power controller when the required accuracy level of the electrolysers' power performance is high.

The developed standardized test protocols can benefit multiple stakeholders. The grid operators are made aware of the potential capability of the electrolyser to support powersystem operation by offering quality services. For electrolyser manufacturers, applying the protocols will guide the design and development of new products. A wide adoption of the standardized test protocols will accelerate the market penetration of electrolysers and facilitate green-energy transition.

As the test protocols are primarily developed from the aspect of grid-service qualification, the protocols in principle can also be applied to testing the grid-service potential of other kinds of electrical technologies, such as a battery or an electric vehicle. This is because the grid operators make no exception to the grid-service providers as long as they can fulfil the technical requirements. Combining the grid-service tests with other electrolyser tests such as durability and degradation tests is therefore strongly recommended in order to fully quantify the potential of electrolysers for grid services. Further, both electrolyser technology and grid-service requirements will evolve over time, so amendment of the developed protocols is foreseeable from time to time.

Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No. 735485. This joint undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY.

Conflict of Interest

None declared.

References

[1] Bertsch J, Growitsch C, Lorenczik S, *et al*. Flexibility in Europe's power sector: an additional requirement or an automatic complement? *Energy Econ* 2016, 53:118–31.

[2] Becker S, Rodriguez RA, Andresen G, *et al*. Transmission grid extensions during the build-up of a fully renewable pan-European electricity supply. *Energy* 2014, 64:404–18.

[3] Huber M, Desislava D, Hamacher T. Integration of wind and solar power in Europe: assessment of flexibility requirements. *Energy* 2014, 69:236–46.

[4] Qadrdan M, Ameli H, Jenkins N. Efficacy of options to address balancing challenges: integrated gas and electricity perspectives. *Appl Energy* 2017, 190:181–90.

[5] Cai H, You S, Wang J, *et al*. Technical assessment of electric heat boosters in low-temperature district heating based on combined heat and power analysis. *Energy* 2018, 150:938–49.

[6] Haas J, Cebulla F, Cao K, *et al*. Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems–a review. *Renew Sust Energ Rev* 2017, 80:603–19.

[7] Meibom P, Hilger KB, Madsen H, *et al*. Energy comes together in Denmark: the key to a future fossil-free Danish power system. *IEEE Power Energy Mag* 2013, 11:46–55.

[8] Dincer I, Acar C. Review and evaluation of hydrogen production methods for better sustainability. *Int J Hydrogen Energ* 2015, 40:11094–111.

[9] Hanley ES, Deane JP, Gallachóir BÓ. The role of hydrogen in low carbon energy futures: a review of existing perspectives. *Renew Sust Energ Rev* 2018, 82:3027–45.

[10] de Valladares MR. *Global Trends and Outlook for Hydrogen*. International Energy Agency (IEA), 2017. https://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_Dec2017_WEB.aspx.

[11] *Study on Early Business Cases for H_2 in Energy Storage and More Proudly Power to H_2 Applications*. Technical report P2H-BC/4NT/0550274/000/03. Brussels: Fuel Cells and Hydrogen Joint Undertaking (FCHJU), 2017. https://www.hinicio.com/inc/uploads/2018/06/P2H_Full_Study_FCHJU.pdf.

[12] Götz M, Lefebvre J, Mörs F, *et al*. Renewable power-to-gas: a technological and economic review. *Renew Energy* 2016, 85:1371–90.

[13] Troncoso E, Newborough M. Electrolysers for mitigating wind curtailment and producing 'green' merchant hydrogen. *Int J Hydrogen Energ* 2011, 36:120–34.

[14] Guinot B, Montignac F, Champel B, *et al*. Profitability of an electrolysis based hydrogen production plant providing grid balancing services. *Int J Hydrogen Energ* 2015, 40:8778–87.

[15] Marcuello P. *Improvements to Integrate High Pressure Alkaline Electrolysers for Electricity/H_2 Production from Renewable Energies to Balance the Grid—Publishable Summary Report. Technical report*. Huesca: Foundation for Hydrogen in Aragon, 2014.

[16] Bertuccioli L, Chan A, Hart D, *et al*. *Development of water electrolysis in the European Union. Technical report*. Brussels: Fuel Cells and Hydrogen Joint Undertaking (FCHJU), 2014.

[17] Homepage for Hybalance project. http://hybalance.eu/ (26 June 2020, date last accessed).

[18] Homepage for Balance project. https://www.balance-project.org/ (26 June 2020, date last accessed).

[19] Homepage for Demo4grid project. https://www.demo4grid.eu/ (26 June 2020, date last accessed).

[20] Homepage for QualyGridS project. http://www.qualygrids.eu/ (26 June 2020, date last accessed).

[21] Gerwen RV, Heer HD. *Position Paper Flexibility Value Chain. Technical report*. Universal Smart Energy Framework (USEF), 2015. https://www.usef.energy/app/uploads/2016/12/USEF_PositionPaper_FlexValueChain-vs1.pdf (26 June 2020, date last accessed).

[22] ENTSO-E. *Electricity Balancing in Europe: An Overview of the European Balancing Market and Electricity Balancing Guideline*. The European network of transmission system operators for electricity (ENTSO-E), 2018. https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Network%20codes%20documents/NC%20EB/entso-e_balancing_in%20_europe_report_Nov2018_web.pdf (26 June 2020, date last accessed).

[23] TRM/LBK. *Prequalification of Units and Aggregated Portfolios. Technical Report Doc. 13/80940-106—Offentlig/Public*. Energinet, 2018. https://en.energinet.dk/-/media/64C3F7B327354828AFE21B6154FCFFF7.pdf?la=en&hash=D30F369243ADE22C5895E60F070D9598A4602128 (26 June 2020, date last accessed).

[24] You S, Træholt C, Marcuello P, *et al*. *Grid Service Catalogue for Water Electrolysers. Technical Report*. QualyGridS Consoritum, 2017. http://www.qualygrids.eu/app/uploads/sites/5/2017/02/Deliverable-1.1-Electrical-Grid-Service-Catalogue-for-Water-Electrolysers-27-11-2017.pdf (26 June 2020, date last accessed).

[25] Reissner R. *Unified and standardized qualifying tests of electrolysers for grid services*. In: Stakeholder Advisory Board Workshop, 2019. https://www.qualygrids.eu/app/uploads/sites/5/2019/12/2019.12.02-Test-protocols-Stakeholder-Advisory-Board-Workshop-31.10.2019.pdf (26 June 2020, date last accessed).