# H2ME 2, D4.11:
# Assessing the current role of electrolysers in the provision of grid services

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FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

# WORK PACKAGE SUMMARY/OBJECTIVES

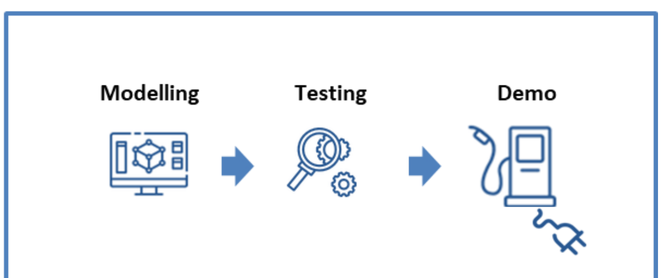
## Assess the capability of electrolyser-HRS to monetize grid services

- Understand and collect data on grid services in France, Germany and UK
- Electricity price and balancing services scenarios for future power systems
- Techno-economic modelling of the electrolyser-HRS

## Assess the capability of electrolyser-HRS to provide grid services

- Develop test protocols based on technical requirements provided by TSO
- Evaluate the answer response of the electrolyser-HRS to these tests
- Real world demonstration based on TSO signal

**H2Me2 – WP4**



# H2ME 2 D4.11: Assessing the current role of electrolysers in the provision of grid services

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# D 4.11 Executive Summary (1/2)

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**Role of grid services for the roll out of green hydrogen**

- Grid service provision could **reduce the cost of hydrogen by up to 10%**.
- Grid services are likely to play a **transitory role** in the roll out of electrolysers as markets for these services are shallow and get saturated quickly.

**Key grid services which electrolysers can provide**

- Key grid services relevant for electrolysers are **balancing services procured by the** Transmission System Operator (**TSO**) and **internal load balancing** at large industrial sites.
- **Balancing services** can be divided into Frequency Containment Reserve (FCR), automated and manual Frequency Restoration Reserve (aFRR and mFRR), and Replacement Reserve (RR). These differ by the **full activation time**, the time by which the contracted capacity can be fully activated after a signal from the TSO.
- Installing an electrolyser for **internal load balancing** can help industrial sites to reduce grid fees as well as imbalance charges.

**Developments in key grid services markets**

- **Batteries** have started to **dominate** some markets for **balancing services**, especially those with short activation times. This trend is expected to continue due to batteries' low cost of providing such services which will make it very challenging for electrolysers to compete in these markets.
- **Harmonisation and integration** of balancing markets across European countries is progressing but some differences in products and procurement processes currently remain.
- **Congestion management** has become a major cost component of system operation due to renewable expansion.
- **Local flexibility markets** run by Distribution System Operators (**DSOs**) can contribute to cost efficient congestion management and could potentially provide attractive revenue opportunities.
- But these markets are only starting to emerge and still immature.

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# D 4.11 Executive Summary (2/2)

Hydrogen Mobility Europe

**Technical requirements of grid services**

- **Standard test protocols** have been developed in the Qualygrids project which could allow electrolysers to be prequalified for balancing provision in a wide range of European countries.
- If integrated in international standards and widely adopted, such **protocols could guide manufacturers** in development of electrolyser design and capabilities.

**Technical capabilities of electrolysers**

- **PEM as well as alkaline electrolysers have the technical capabilities** to provide balancing services (FCR, aFRR, mFRR, and RR) provided they are equipped with appropriate controlling technology.
- PEM electrolysers have been shown to be **capable to provide internal load balancing**.

**Current role of electrolysers in grid services markets**

- Currently **electrolysers don't play a tangible role in grid services markets.**
- Projects in which electrolysers are providing or planning to provide balancing services in a **commercial** setting are **only starting to emerge**, the most prominent being HyBalance, H2Future, REFHYNE, and Demo4Grid.
- The **capacity** of these electrolysers is **small compared to the demand** for grid services, e.g. the REFHYNE electrolyser's capacity represents less than 2% of the demand for FCR in Germany.
- **Electrolysers** in the HyBalance and H2Future projects have been **prequalified** by the TSO for **all types of balancing services** and are currently participating in balancing markets in Denmark and Austria, respectively.

# H2ME 2 D4.11: Assessing the current role of electrolysers in the provision of grid services

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# This report examines the current role of electrolysers in grid services markets

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**Overview and context in H2ME 2 project**

- Key objective of work package 4 of H2ME 2 is to understand the **role of electrolysers** in providing valuable grid services to a **future energy system** with high penetration of variable renewable energy sources.
- The work package also aims to understand the **revenues** which electrolysers could expect **from the provision of grid services** and how this would improve their **business case**.
- Within this context, this report examines the **current role** of electrolysers in grid services markets.

**Types of grid services electrolyser could provide**

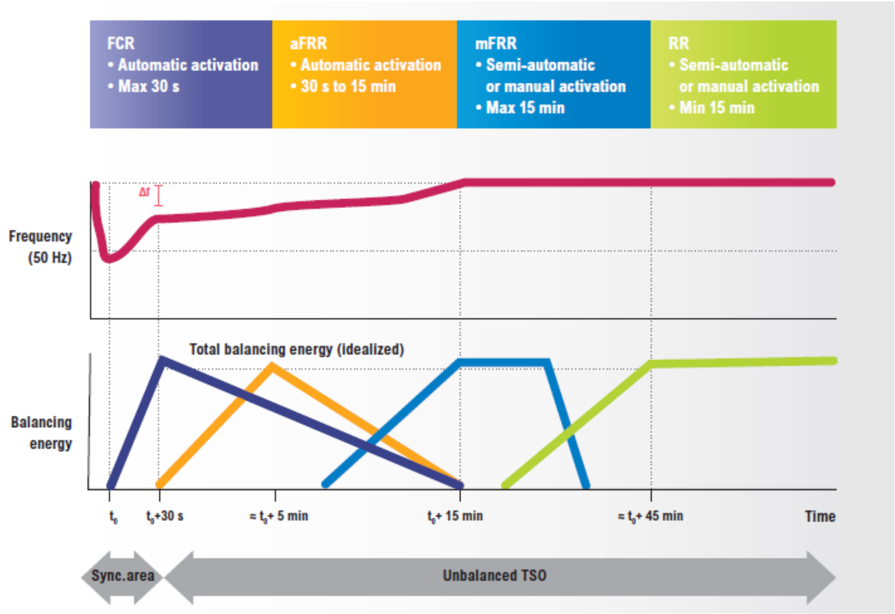
- The grid services deemed most relevant for electrolysers in the short to medium term are **balancing services** to the Transmission System Operator (TSO) and **internal load balancing** at large industrial sites.
- Emerging **local flexibility markets** run by Distribution System Operators (DSOs) have also started to emerge and deemed to be potentially attractive for electrolysers.

# Structure of this report

**Report structure**

- **Section 2** discusses recent developments in key **grid services markets**
- **Section 3** explores **technical requirement**s of the grid services most relevant for electrolysers
- **Section 4** lists the reported **capabilities of electrolysers** to comply with technical requirements of grid services and introduces the **key electrolyser projects** in Europe which are currently providing grid services or preparing to provide grid services on a commercial basis.
- **Section 5** draws the main **conclusions** of the report

# Overview of grid services

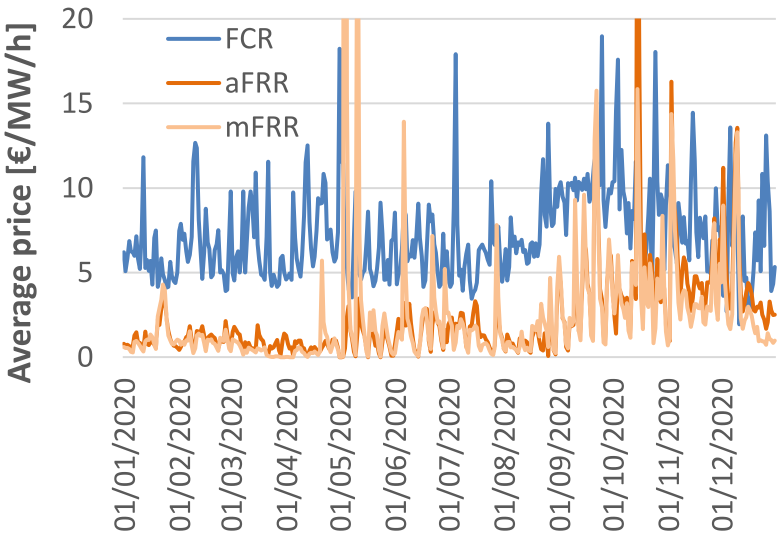



- Among the grid services most relevant for electrolyser projects in the short to medium term are **balancing services**, procured by the Transmission System Operator (TSO)
- These balancing services can be divided into four categories: **Frequency Containment Reserve (FCR), automated and manual Frequency Restoration Reserve (aFRR and mFRR),** and **Replacement Reserve (RR)**
- One main distinction between those types of services is the **full activation time (FAT)**, the time by which a response to a signal from the TSO (or the grid frequency) can be fully activated (cp. graph on the left[1])
- The following slides explore some key developments in European balancing markets and two further markets deemed relevant for electrolysers
  - **Local flexibility markets** run by **Distribution System Operators (DSOs)**
  - **Internal load balancing** for large industrial sites
- A comprehensive review of grid services markets in several European countries can be found in (Qualygrids, 2019) and (H2ME 2, 2021)

1) ENTSO-E, 2018

# Balancing services with faster response offer higher revenues but markets are smaller

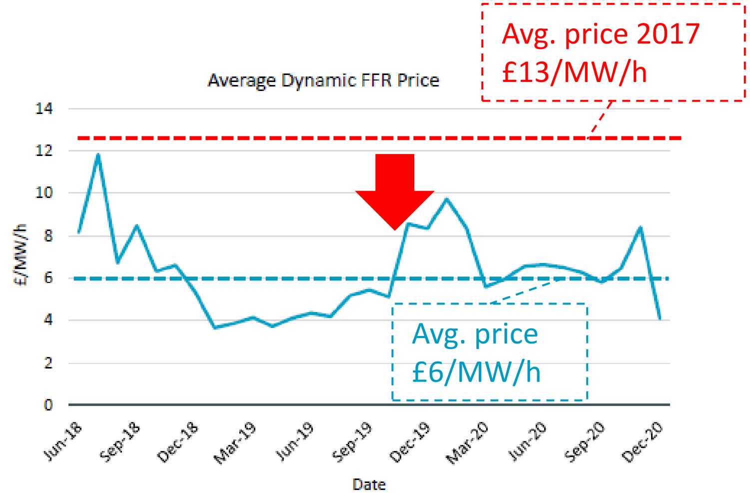
| Service | Demand (MW) | Price (€/MW/h) | Product length (h) | Auction cycle |
|---|---|---|---|---|
| FCR | 605 | 7.2 | 4 | Daily |
| Positive aFRR | 1,900 | 2.3 | 4 | Daily |
| Negative aFRR | 1,800 | 2.0 | 4 | Daily |
| Positive mFRR | 1,400 | 2.6 | 4 | Daily |
| Negative mFRR | 1,025 | 1.2 | 4 | Daily |

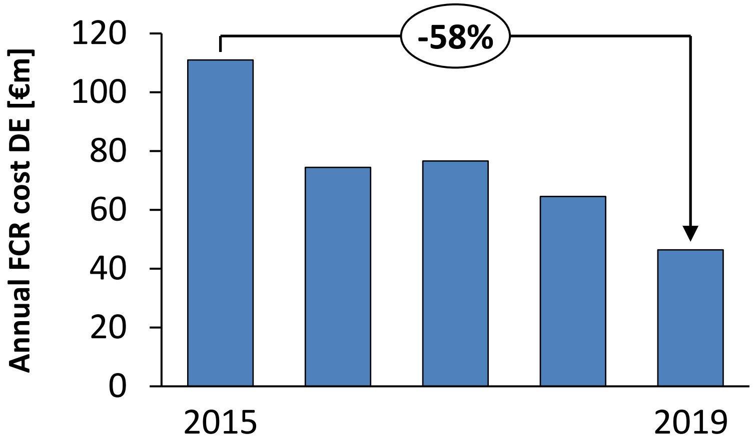



- Balancing services which require **shorter full activation time** and typically offer **higher revenues** than services with longer activation times
- The left table shows current market size and prices of balancing services in Germany[1]
- Balancing markets are **relatively small** (e.g. 605 MW corresponds to less than 1% of peak demand of around 80GW[2] in Germany)
- Important to note that **FCR** is a **symmetric** service, i.e. the price paid is per MW upward AND downward response
- **FCR** offers the **highest revenues** but is the smallest market in terms of capacity procured
- **aFRR** requires **shorter activation** times **than mFRR** and typically offers slightly **higher revenues[3]**
- Left graph shows daily average prices of FCR, positive aFRR and mFRR in Germany in 2020
- **Significant fluctuation** of prices over year, with **mFRR** showing **highest fluctuation**, followed by aFRR and FCR[4]
- **Difficult to predict** bidding behaviour and subsequently auction outcomes

1) In Germany the TSO procures no RR as beyond a 1h time limit, imbalance management is the responsibility of market participants; 2) BDEW 2020; 3) Avg. positive mFRR price higher than positive aFRR price in 2020 due to extreme prices in May (cp. graph), but on most days aFRR price is higher than mFFR price (cp. graph, median of pos. aFRR is 1.4 vs 1.2 for mFRR); 4) stand. dev.: mFRR: 7.2; aFRR: 3.0; FCR: 2.7)

# FCR prices have been reduced in recent years, in part due to emergence of battery storage




- **FCR prices** have been **significantly reduced** in several European markets in recent years
- **In Britain**, prices for dynamic Firm Frequency Response (FFR), a FCR type service, have been reduced by **more than 50%** since 2017 (left[1])
- **In Germany,** the FCR market has been reduced by **more than 50%** in the last 5 years (right)
- This is to a significant extent driven by the emergence of **batteries** in these markets, which are able to provide this service **faster and at lower marginal cost**[2] than incumbent technologies
- **Installed battery storage capacities** in GB (1.1GW) and DE (280MW) have become **significant** compared to the respective FCR requirement (around 1GW[3] and 600MW[4] respectively)
- **Dominance of batteries** in FCR markets[5] is expected to continue due to close match of service requirements and technology's capabilities
- Batteries are likely to set FCR prices and will do so according to the **cost of** foregone **opportunities** in other markets (other balancing services, wholesale market, etc)[1,6]

1) LCP, 2021; 2) Less than £1/MW/h, cp. (Arenko, 2021); 3) National Grid ESO, 2021; 4) Bundesnetzagentur, 2021; 5) UK TSO National Grid ESO has introduced a new FCR type service which is currently exclusively provided by batteries, requiring initial response after 0.5s and full response after 1s, cp. (National Grid ESO, 2019); 6) Lempriere, 2019

# Increasing integration of European balancing markets puts downward pressure on prices

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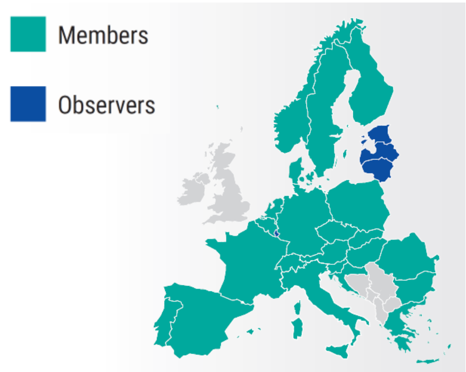
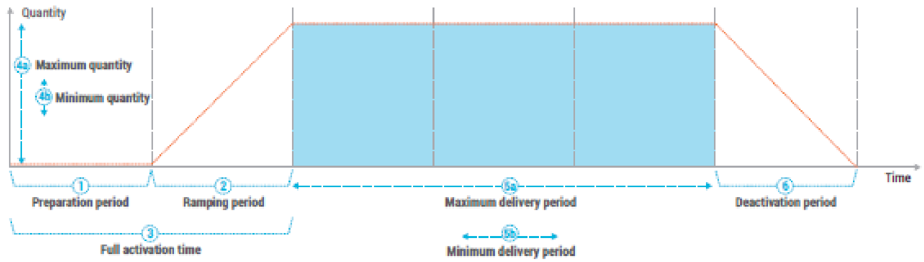
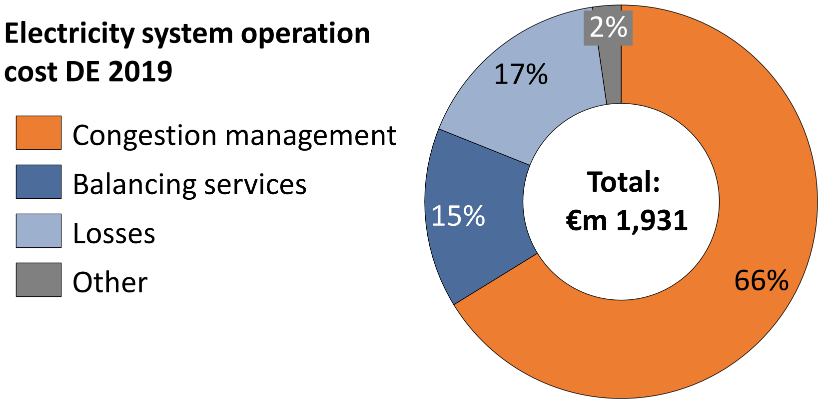


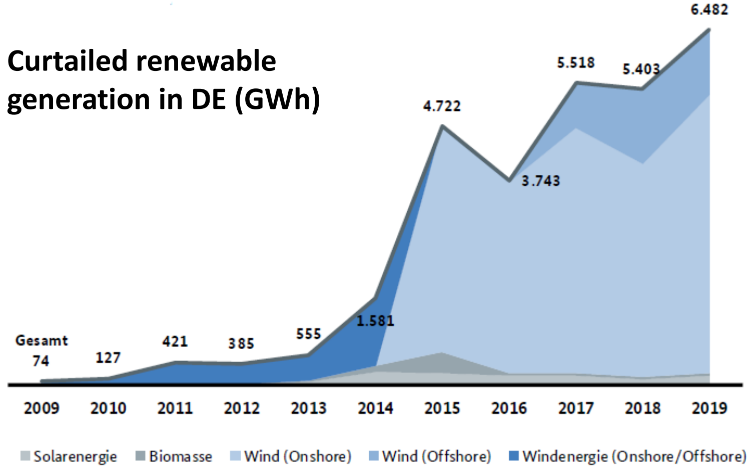




- European member states aim to **integrate** their TSOs' **balancing markets** to increase competition, liquidity, and efficiency
- The Electricity Balancing (EB) Regulation, adopted in 2017, requires TSOs to establish **platforms for cross border exchange of balancing energy** for aFRR (PICASSO), mFRR (MARI), and RR (TERRE) services (above left graph shows members of PICASSO)
- TERRE has gone live in 2020[1], while PICASSO and MARI are planned to go live in 2022[2]
- Eight countries (DE, FR, NL, BE, DK, CH, AT, SI) are furthermore currently procuring **FCR** over a **common platform**
- The EB Regulation requires TSOs to **harmonise** their aFRR, mFRR, and RR **procurement of balancing services** through standardization of products (product length, activation time, cp. right figure above) and procuring (pricing, minimum bid size, move to daily auctions)
- TSOs have to implement the balancing market design as specified by ACER by July 2022[3]
- **Currently some differences** in technical requirements of balancing services between countries **remain**[4]
- Integration of balancing markets is expected to reduce procured volumes due to increased efficiency and put **downward pressure on prices** due to increased liquidity and competition[5]

1) SP Global, 2020; 2) Bundesnetzagentur, 2021 3) ENTSO-E 2020 4) (Qualygrids, 2020 a), pp. 88 lists technical requirements and procurement methods in several EU countries; 5) (Bundesnetzagentur 2016), (Bundesnetzagentur 2021)

# Electrolysers could help manage increased grid congestion driven by RES expansion

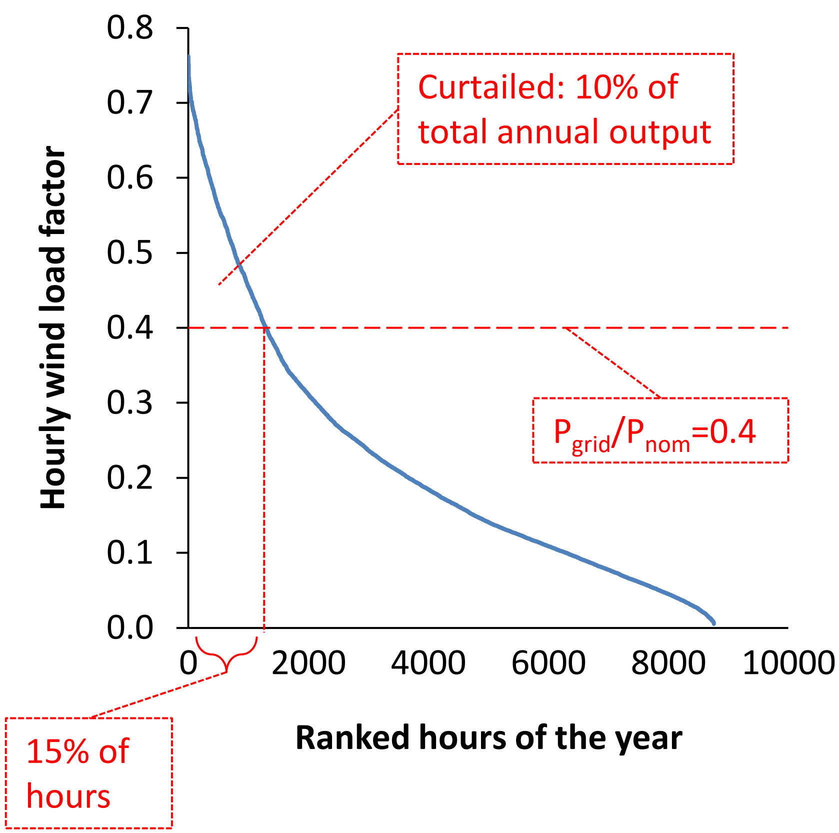



- Transition to highly renewable supply means location of supply relative to demand is changing and requires significant transformation of electricity grids
- In several European countries **transition of electricity grids behind transition of supply**, leading to **high congestion management costs** (cp. above left, breakdown of system costs in DE[1], similarly congestion management 54% of system operation cost in GB in 2019/20[2])
- To manage grid, wind energy is increasingly being curtailed (cp. right chart showing renewable curtailment in Germany[1], wind curtailment corresponded to 5% of wind output 2019)
- Majority of curtailed wind energy is of wind farms connecting at **distribution grid** (81% in DE in 2019[3])
- **If located in the right area** of the electricity grid, electrolysers could contribute to managing grid congestion either by turning up their consumption in times of high renewable output or turning down their consumption in times of peak demand.

1) Bundesnetzagentur, 2021; 2) NG ESO, 2020; 3) while caused by congestion on the transmission grid, cp. (Bundesnetzagentur, 2021)

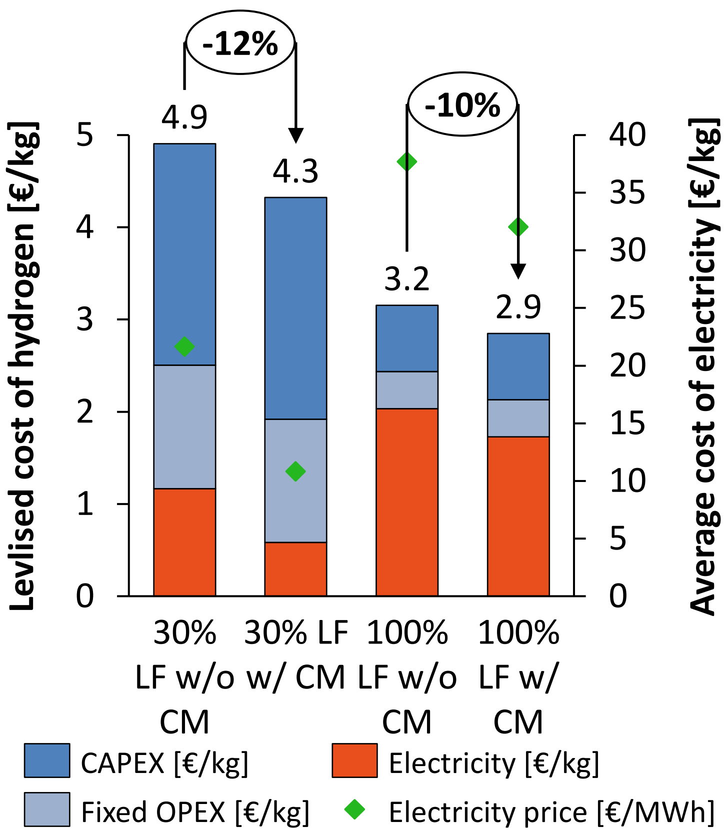
# Curtailment of wind output above 40% of rated capacity leads to ca. 10% curtailment rate




- Electrolyser **currently don't provide congestion management** (CM) as a commercial service
- To estimate potential savings of electrolysers by providing CM in form of **demand turn up**, we use a similar approach as in (Qualygrids, 2019)
- Assume wind farm owner in **export constrained zone** of distribution grid installs electrolyser next to wind farm (private wire)
- Assume in hours of wind farm curtailment all electrolyser consumption can be supplied by curtailed wind output
- Assume **electricity** consumption of electrolyser is **free in hours of curtailment** as wind farm is compensated for curtailed output (at least 95% of lost revenue in DE) by distribution grid owner
- Assume ratio of 40% of grid export capacity $P_{grid}$ available to wind farm to nominal wind farm capacity $P_{nom}$
- Left figure shows hours of the year 2019 ordered by onshore wind fleet output in DE[1]
- $P_{grid}/P_{nom}$ = **40%** would lead to curtailment in **1,294 hours**, corresponding to **10% of total output being curtailed**, **twice the average curtailment** of onshore wind in DE in 2019[2]

1) Data from (Bundesnetzagentur, 2021 b); 2) Bundesnetzagentur, 2021 a;

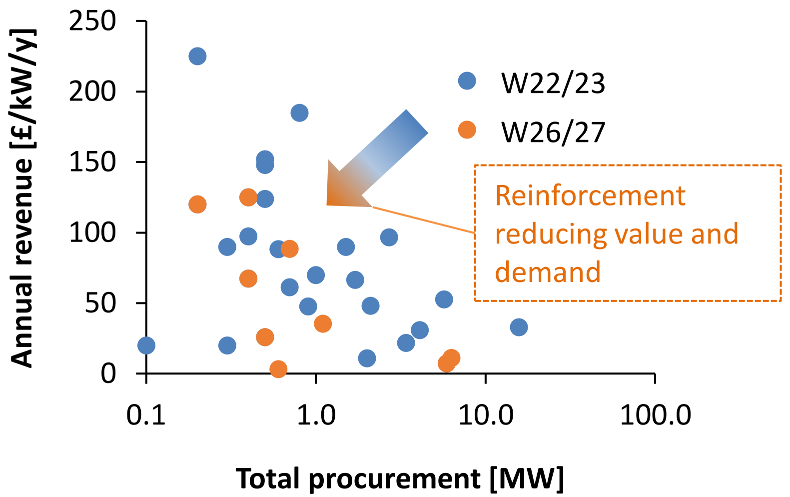
# Consumption of wind curtailment could reduce H2 cost by ca. 10% in case of high curtailment

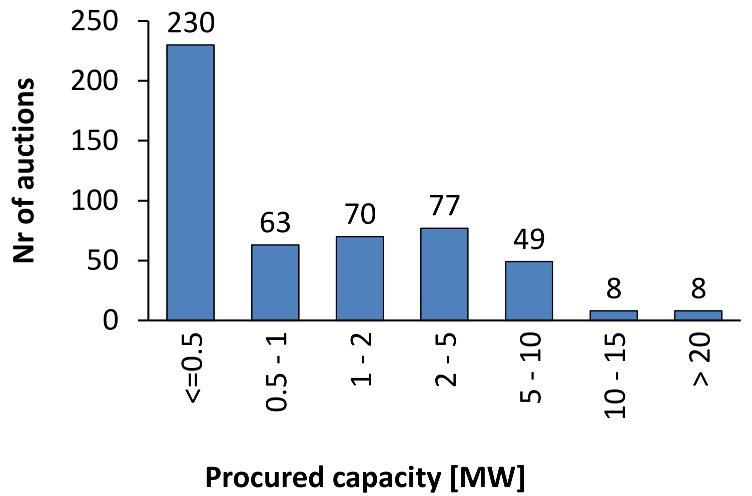



- **Impact of consumption of curtailed wind energy**, a form of congestion management (CM), **depends on electrolyser load factor**
- **At 30% load factor (LF)**[1], curtailed wind energy (in 15% of annual hours) is 50% of total electricity consumption, thus **electricity costs** are **halved** with CM
- But **H2 cost dominated by CAPEX and OPEX**[2] and even without CM electrolyser is already consuming electricity at a low average price, choosing 30% of lowest cost hours[3]. **Total cost reduction** is **12%**
- **At 100% load factor**, curtailed wind energy is only 15% of total consumption
- **Electricity costs reduced by 15%, similar total cost reduction** (**10%**) as **CAPEX and OPEX** only **small share** of total H2 cost due to distribution of fixed cost among more kg H2 and **higher average cost of** consumed **electricity** as electrolyser can't avoid high price hours
- **Higher load factor** leads to lower total cost, thus **preferable**
- In the future, renewable oversupply rather than network constraints[4] could become dominant driver of curtailment and lead to **extended periods of zero** marginal **cost** electricity, which could make lower load factors attractive to electrolysers[5].

1) Assuming electrolyser does only operate at 100% or 0% of rated capacity, therefore load factor is the same as the share of annual hours in which electrolyser is operational; 2) cp. appendix for assumptions 3) based on 2019 electricity wholesale prices in DE, using data from (Bundesnetzagentur, 2020 b); 4) TSOs can allow for up to 3% curtailment of annual output of wind and solar plants in their network planning, i.e. only have to ensure network related curtailment rates don't go above 3% (BMWi, 2015); 5) cp. e.g. (Ruggles et. al, 2021)

# Local flexibility markets run by DSOs are only starting to emerge

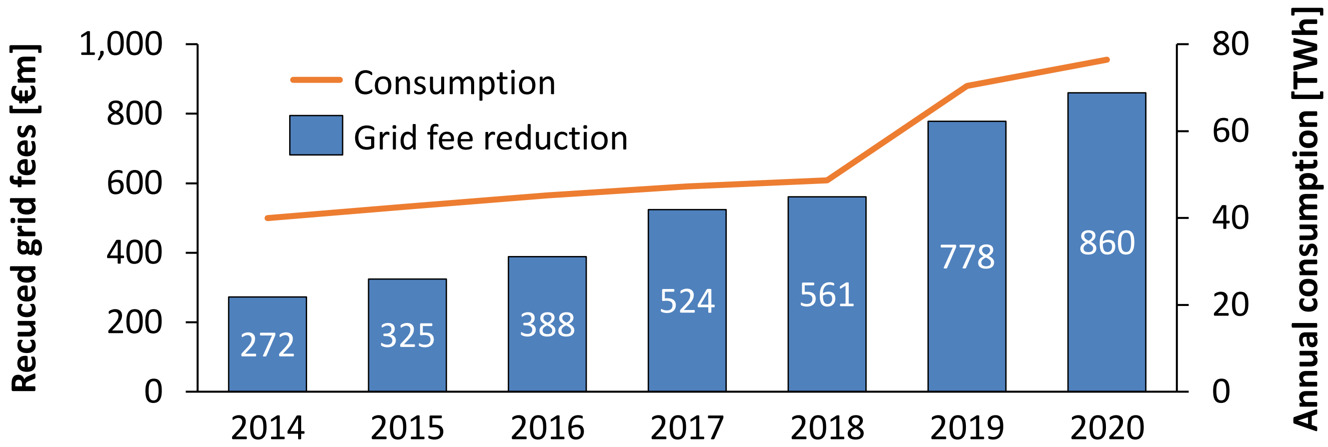



- **Local markets for flexibility** run by DSOs are only starting to emerge and **still immature**; design and engagement of providers is still evolving
- Left: expected annual revenues in different constrained zones of a DSO's licence area in the UK (UKPN) in two different years[1]
- Local flexibility markets can offer **attractive revenues of around £40/kW/y**
- But value of flexibility **highly location specific**, depending on the avoided cost of reinforcement in the particular part of the distribution grid (ranging between £0-230/kW/y, cp. left graph)
- Value also **time specific** as distribution reinforcement will reduce demand for flexibility (left graph)
- Furthermore in many auctions **procured capacity** will be **low** (less than 1MW per auction, cp. right graph above[2]) making these markets less relevant for larger multi-MW assets
- **Unclear** if **electrolysers** will be **available for demand turn down services revenues** in import constrained zones as they constitute new demand and would thus contribute to the import constraint.

1) UKPN, 2021; 2) Piclo, 2021

# Internal load balancing could improve electrolyser business case at large industrial sites




- At large industrial sites an **electrolyser could be used** for internal load balancing **to smoothen** the site's **electricity consumption**
- In Germany, stable and permanent electricity consumption by **energy intensive** industrial sites is deemed to contribute to grid stability and thus rewarded.
- Electricity consumers with an annual consumption higher than 10GWh and at least 7,000 (7,500, 8,000) full load hours are entitled to a **grid fee reduction[1] by up to 80%** (85%, 90%)[2]
- In the past years, increasing number of industrial consumers has been granted the grid fee reduction, **volume of reductions** for energy intensive businesses **has risen to €860m** in 2020[3]
- Installing an electrolyser on an industrial site and running it only outside the peak consumption hours of the plant can **increase the full load hours** of the plant and thus **contribute to a grid fee reduction**.
- Grid fee reduction **specific to German context**, but fee reductions due to consumption profiles deemed valuable for grid operation also exist in other countries, e.g. France and Netherlands[4]
- The electrolyser can also be used to reduce deviations of a site's actual to planned consumption and thus **reduce imbalance costs** the site has to pay for such deviations

1) Referring to total grid fees, i.e. transmission as well as distribution, depending on the voltage level that consumer is connecting to; 2) Bundesministerium für Justiz und Verbraucherschutz, 2021 a; 3) corresponding to 77 TWh consumption at 571 sites, (Bundesnetzagentur, 2021); 16%of total electricity consumption (475 TWh, (Bundesnetzagentur, 2021 b)); 4) PWC, 2020

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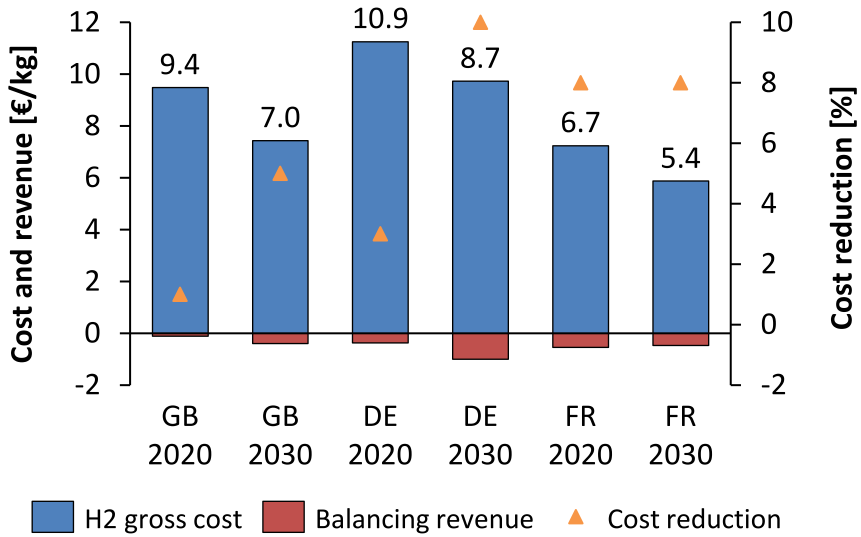
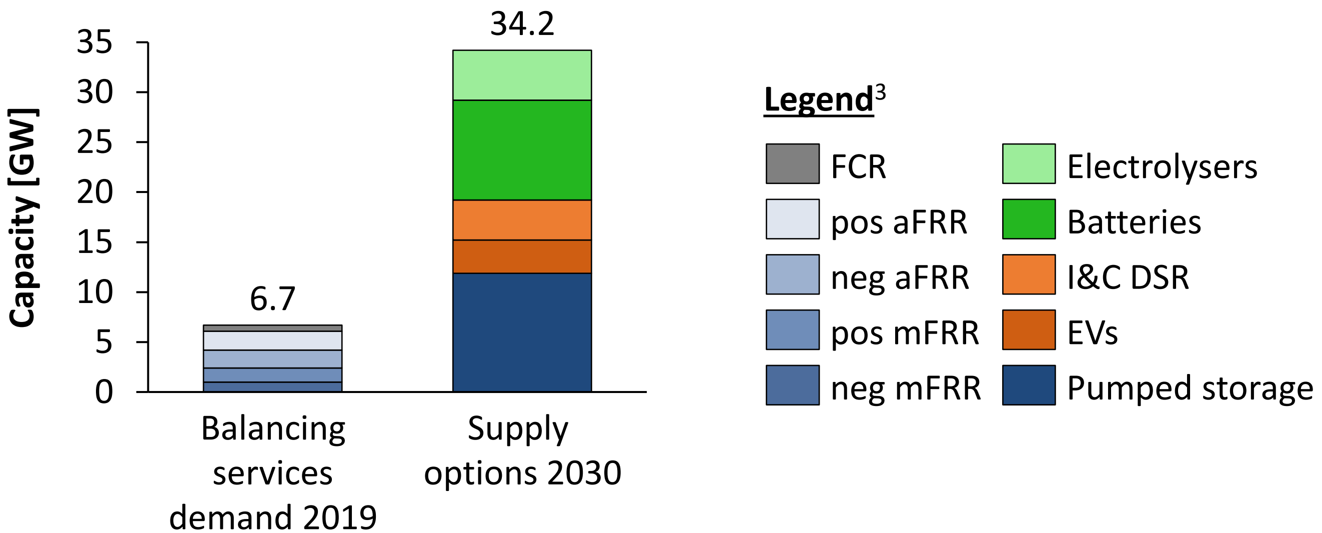
# Provision of grid services could reduce H2 production cost by up to 10%




- As derived in recent analysis by Element Energy[1] (graph above) as well as Lucerne University[2], **balancing services provision** could **reduce the cost of hydrogen by up to 10%**
- Similarly we have estimated a **cost reduction of up to 10% by congestion management** in form of consumption of curtailed output of a windfarm **in the near term** (slide 16)
- While provision of grid services might constitute a material improvement of electrolyser business cases in some projects, it is **unlikely to be a main revenue** stream of an electrolyser business model
- Furthermore demand for grid services is limited and markets for grid services are likely to be very competitive (see following slide)

1) Element Energy, 2020; 2) Qualygrids, 2019;

# Markets for grid services are shallow and can get saturated very quickly




- Grid services are likely to only play a **transitory role** in the roll out of electrolysers as markets for these services are **shallow** and get **saturated quickly**
- Despite high VRES growth, **demand for balancing services has decreased** significantly in the last 10 years in Germany[1], due to (among others) integration of and increased competition in balancing markets, improved renewable output forecasting, increased intraday trading
- **Multiple low carbon supply options** for balancing services are likely to lead to a high level of competition in these markets in the medium term (cp. above[2])
- While **demand for congestion management** has increased significantly in recent years, completion of ongoing grid reinforcement is **expected to reduce** demand in the medium term
- **Grid service provision** could support business models of early electrolyser projects but is **unlikely to play a major role** in the mass roll out of electrolysers

1) Bundesnetzagentur, 2021 a; 2) Sources: balancing services demand: Bundesnetzagentuer, 2021 a; supply options: see appendix; 3) EVs = electric vehicles, I&C DSR = industrial and commercial demand side response

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# Qualygrids: standard test protocols for electrolysers

| Key project data[1] | |
|---|---|
| Electrolyser capacity | 10kW - 1 MW |
| Electrolyser technology | Alkaline + PEM |
| Location | Various |
| H2 end use | Various |
| Project period | 2017-2020 |
| Start of operation | Various |
| Project partners | DLR, NEL, DTU, ITM, Ha[2] |
| Overall budget | €2.8m |

**Project overview**

- Aim of Qualygrids: develop **standardised test protocols** for electrolysers
- Developed **tests** have been **conducted with** a range of **demo electrolyser installations**

**Grid services investigated**

- **FCR, aFRR, mFRR, and RR** determined as most relevant grid services for electrolysers
- **DSO services** seen as **attractive potential revenue stream** but markets considered immature with insufficient price information[3]

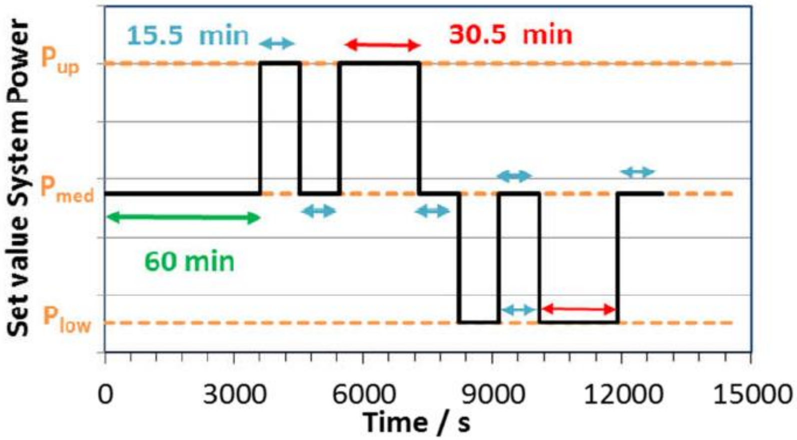
**Standardised testing of electrolysers**

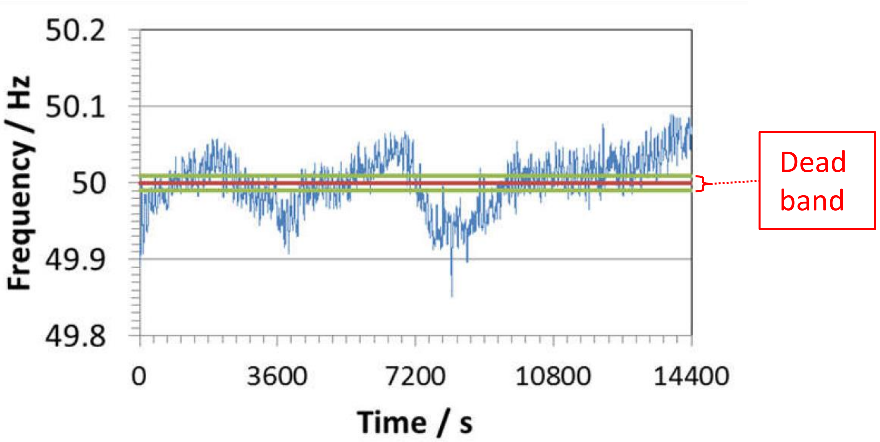
- Based on review of service requirements in a wide range of European countries[4] tests developed, which would allow **qualification in all countries**[5]
- Continuing effort to **integrate tests into international standards**, in collaboration with ISO/TC 197 “Hydrogen Technologies”[6]
- Widely adopted standard protocols could **guide manufacturers** in development of electrolyser design and capabilities[7]

**Following slides summarise tests developed for prequalification for FCR, aFRR, mFRR, and RR.**

1) EU Commission, 2020 a; 2) Further partners: CEA, NEN, IHT; 3) Qualygrids, 2019 4) DE, FR, UK, ES, NL, NO, DK, CH, (Qualygrids, 2020 b); 5) Qalygrids, 2020 d; 6) Qualygrids, 2020 a; 7) Qualygrids, 2020 b

# FCR prequalification requires performance of ramps in 30s and frequency following




<u>**Test for Frequency Containment Reserve (FCR)[1]**</u>

- FCR symmetric service, i.e. suppliers need to provide upward and downward response
- 2 tests to be performed; set point profile of 1st test shown above on the left
- Electrolyser operator specifies boundary operational levels $P_{low}$ and $P_{up}$ in advance; $P_{med}$ is defined as $0.5*(P_{low}+P_{up})$
- Electrolyser has to be able to follow the set point profile with high precision
- <u>**Key performance requirements include**</u>
  - **Ramp rates**: 50% of full ramp up/down (e.g. full ramp up from $P_{med}$ to $P_{up}$, full ramp down from $P_{up}$ to $P_{med}$) within 15s; 100% of ramp up/down in 30s
  - **Power stability:** deviation from set point outside of the ramp up/down periods ≤ 5% * $(P_{med}-P_{low})$
  - **Initial response time:** within 1.5s
- 2nd test requires electrolyser to follow a given frequency profile given in 0.1s resolution within certain constraints (specified acceptable power consumption range for each 0.1s) over a 4h period

1) Qualygrids, 2020 a

# aFRR prequalification requires performance of ramps in 133s (2.2 minutes)

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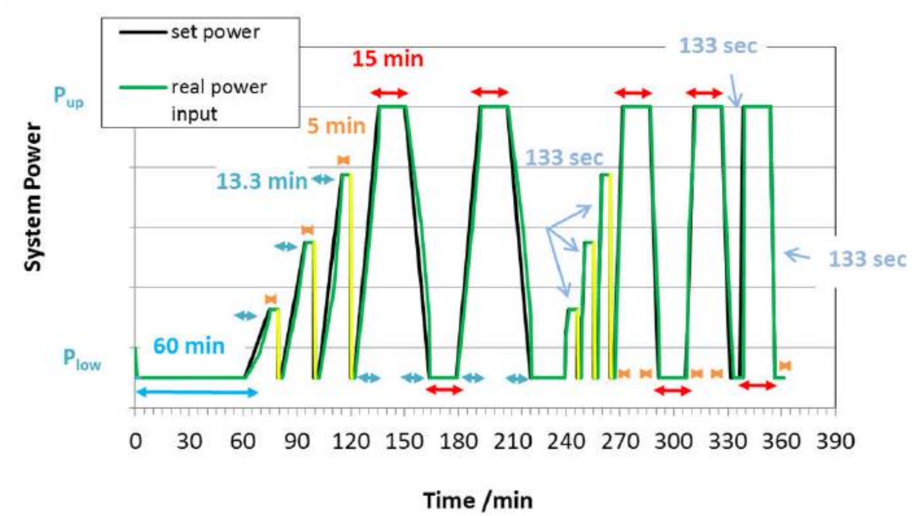


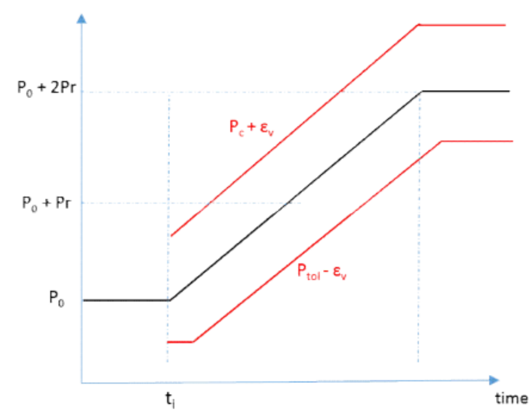


**Test for automated Frequency Restoration Reserve (aFRR)**[1]

- Electrolyser operator specifies boundary operational levels $P_{low}$ and $P_{up}$ in advance;
- **Negative aFRR** (=electrolyser increases consumption on request):
  - **Ramp rates:** electrolyser required to perform ramps of 25%, 50%, 75%, 100% of the full ramp (= $P_{up} – P_{low}$), first in periods of 800s (=13.3 min), then in periods of 133s (upper left graph)
  - **Power stability:** deviation from set point profile $\leq$ 5% * ($P_{up} – P_{low}$) during constant periods, and within an envelope defined by $\varepsilon_v$= 2.5% * ($P_{up} – P_{low}$) during ramping periods (cp. right graph)[2]
- **Positive aFRR** (=electrolyser decreases consumption on request): test protocol and requirements similar to those in the case of negative aFRR, but electrolyser has to perform downward ramps (reducing consumption from $P_{up}$)
- **Aggregated test:** Additional test defined for negative and positive aFRR combined (to save time, if electrolyser plans to provide both positive and negative aFRR)

1) Qualygrids, 2020 a; 2) in both cases sufficient if electrolyser stays within envelope for 95% of the time

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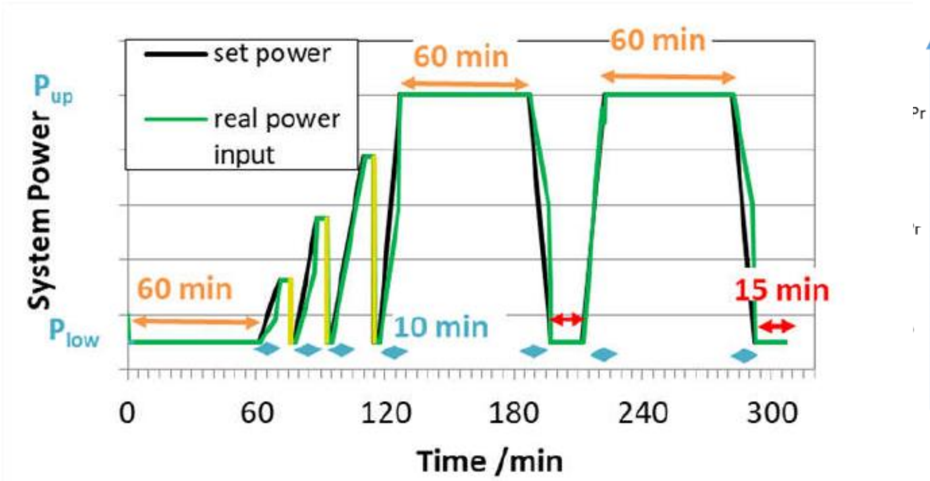
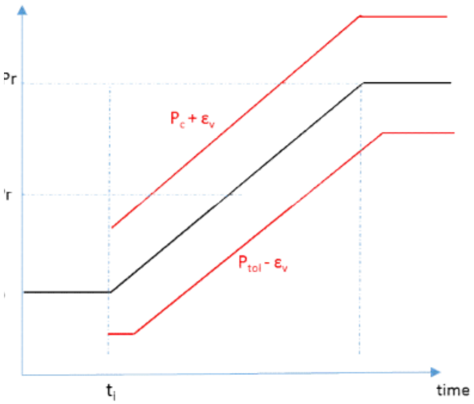
# mFRR requires performance of ramps in 10 minutes



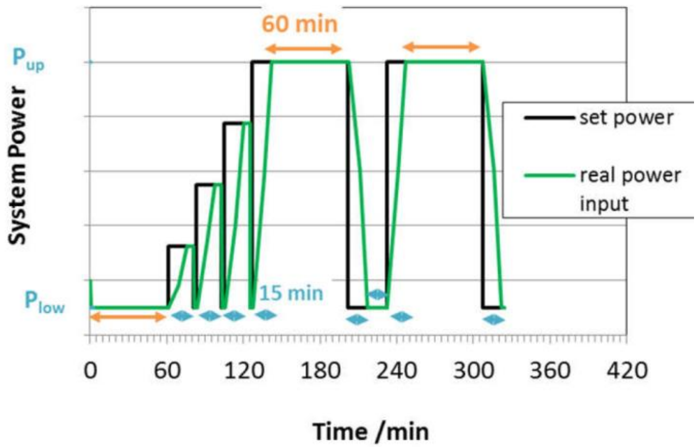



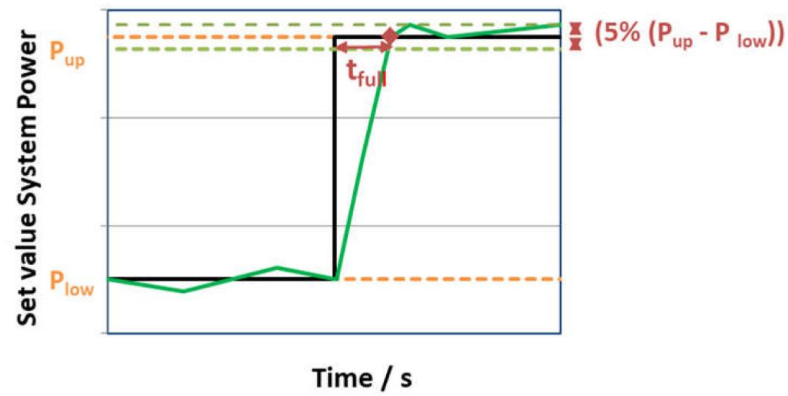

**Test for manual Frequency Restoration Reserve (mFRR)**

- Electrolyser operator specifies boundary operational levels $P_{low}$ and $P_{up}$ in advance;
- **Negative mFRR** (=electrolyser increases consumption on request):
  - **Ramp rates:** electrolyser required to perform ramps of 25%, 50%, 75%, 100% of the full ramp (= $P_{up} – P_{low}$), each in 10 minutes (upper left graph)
  - **Power stability:** deviation from set point profile $\leq$ 5% * ($P_{up} – P_{low}$) during constant periods, and within an envelope defined by $\varepsilon_v$= 2.5% * ($P_{up} – P_{low}$) during ramping periods (cp. right graph)[2]
- **Positive mFRR** (=electrolyser decreases consumption on request): test protocol and requirements similar to those in the case of negative mFRR, but electrolyser has to perform downward ramps (reducing consumption from $P_{up}$)
- **Aggregated test:** Additional test defined for negative and positive mFRR combined (to save time, if electrolyser plans to provide both positive and negative mFRR)

1) Qualygrids, 2020 a; 2) in both cases sufficient if electrolyser stays within envelope for 95% of the time

# RR requires performance of ramps in 15 minutes



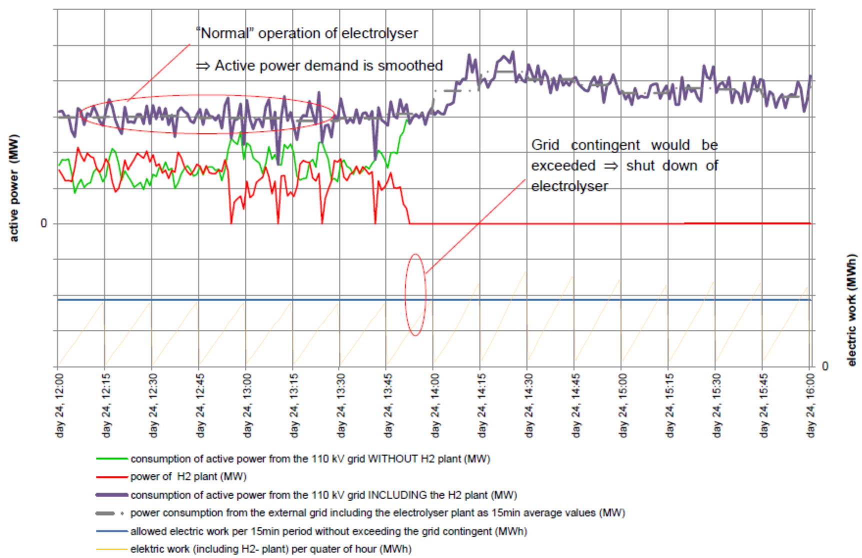




**<u>Test for Replacement Reserve (RR)</u>**[1]

- Electrolyser operator specifies boundary operational levels $P_{low}$ and $P_{up}$ in advance;
- **<u>Negative RR</u>** (=electrolyser increases consumption on request):
  - **Ramp rates:** electrolyser required to perform ramps of 25%, 50%, 75%, 100% of the full ramp (= $P_{up} - P_{low}$), each in 15 minutes (upper left graph)
  - **Power stability:** At full activation level (after ramping up) deviation of electrolyser profile from $P_{up}$ required to stay $\leq$ 5% * full ramp (= $P_{up} - P_{low}$) (upper right graph)
- **<u>Positive RR</u>** (=electrolyser decreases consumption on request): test protocol and requirements similar to those in the case of negative RR, but electrolyser has to perform downward ramps (reducing consumption from $P_{up}$)
- **<u>Aggregated test:</u>** Additional test defined for negative and positive mFRR combined (to save time, if electrolyser plans to provide both positive and negative mFRR)

1) Qualygrids, 2020 a;

# Internal load balancing requires rapid load changes of the electrolyser



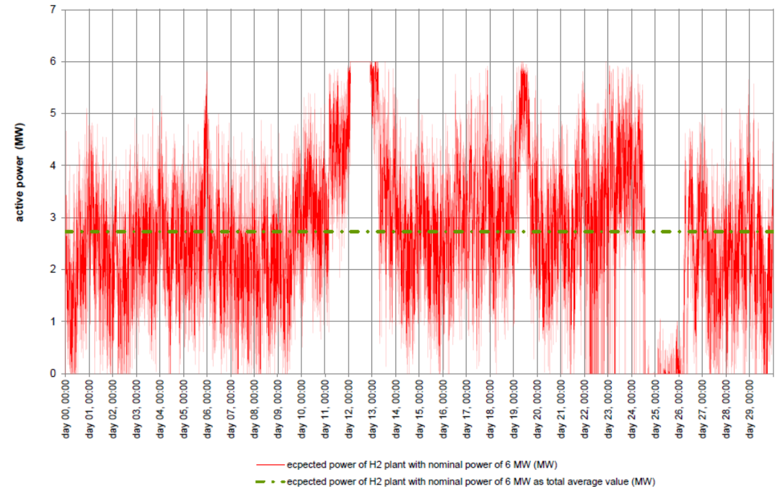




Figure 5: expected power curve of H2 plant (with a nominal power of 6 MW) for the period of 30 days (1min average values) and average power of the electrolyser

- In H2 Future[1] project tests use case in which **electrolyser reduces the imbalances** of the actual total electricity consumption of a steel plant from the electricity grid compared to its scheduled consumption
- **Imbalances** monitored in **15 minute intervals**[2] (cp. grey line in left graph above showing consumption averaged over 15 minute intervals)
- Such internal load balancing requires a **highly responsive operation** of the electrolyser with significant rapid ramping up and down within 15 minute intervals and is furthermore expected to lead to a relatively **low load factor** (below 50% cp. right graph above)
- Alternatively, using the electrolyser to **increase a site's full load hours** (cp. s. 19), would lead to high load factor, as its **consumption** would only be **reduced rarely** (e.g. when an onsite generator trips)
- A **rapid response of the electrolyser** would also be **required** in this case, to ensure the site's contracted peak consumption from the grid is not exceeded.



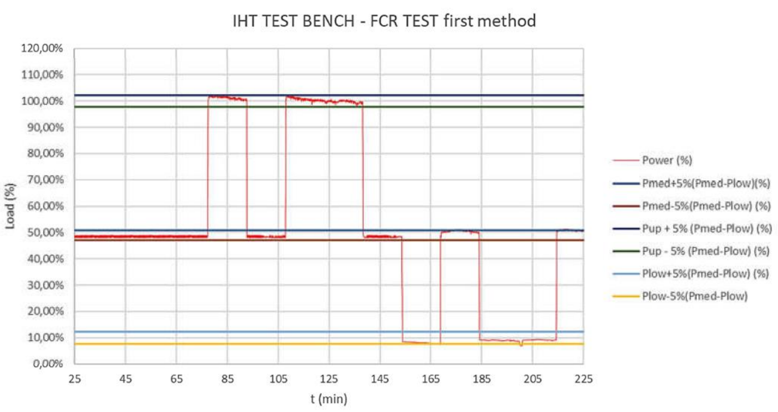
1) Project description in following section on electrolyser projects; 2) standard interval for imbalance settlement as required by the EB Regulation, Article 53 (EU Commission, 2017);

# H2ME 2 D4.11: Assessing the current role of electrolysers in the provision of grid services

# Qualygrids: Alkaline and PEM electrolysers able to provide FCR, aFRR, mFRR, and RR

Hydrogen Mobility Europe

| Institution | Manufacturer | Type | Nominal power (kW) |
|---|---|---|---|
| DTU | ITM | PEM | 28 |
| DLR | Cummins | PEM | 50 |
| DLR | Cummins | PEM | 1,000 |
| FHa | IHT | Alkaline | 10 |
| IHT | IHT | Alkaline | 50 |
| NEL | NEL | Alkaline | 300 |




- In the Qualygrids project, the developed testing protocols for FCR, aFRR, mFRR, and RR were applied to **six demo electrolysers** of both PEM and Alkaline type and sizes ranging from **10kW to 1MW** (left table)
- While not all of the six demo systems were able to pass all tests, the project concluded that with the right setting of system components (e.g. power controller[1]), **both PEM and Alkaline electrolysers can perform all services**
- Left figure shows performance of the tested 50kW alkaline electrolyser in the first FCR test. The electrolyser was run between **10%** ($P_{low}$) and **100%** ($P_{up}$) **of nominal power**. The electrolyser passed the test.

**Minimum bid sizes**

- Qualygrids notes the following typical minimum bid sizes: 2MW for FCR, 5MW for aFRR, 10MW for mFRR, 1.5MW for RR[2]
- Aggregation to exceed minimum bid size threshold is usually allowed but **testing procedure for aggregated loads** still needs **to be determined**[5]

1) PID (proportional-integral-derivative) controller, (Qualygrids, 2020 b); 2) Qualygrids, 2020 a; 5) Qualygrids, 2017;

# Electrolysers currently do not play a tangible role in grid services markets

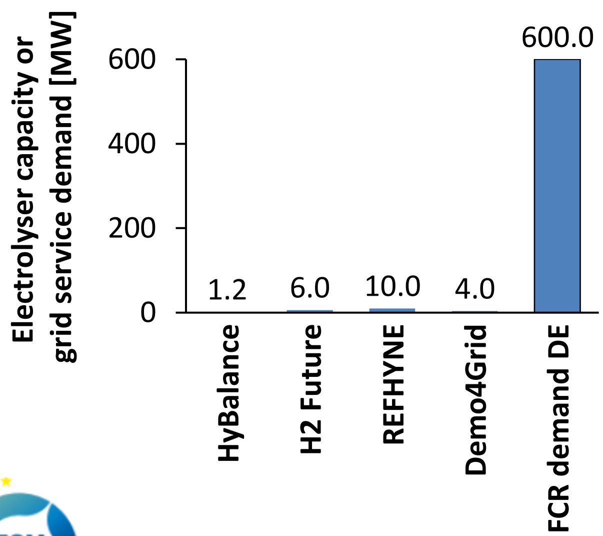
Hydrogen Mobility Europe

DEMO 4GRID

H2FUTURE Green Hydrogen

REFHYNE CLEAN REFINERY HYDROGEN FOR EUROPE

HyBalance




- The **key European projects** in which electrolysers are either already providing grid services on a commercial basis or planning to do so, are <u>HyBalance (Denmark), H2Future (Austria), REFHYNE (Germany), Demo4Grid (Austria)</u>
- While the electrolysers of these projects will be some to the world's largest, their **capacity** is **small compared** to the market size of grid services
- E.g. the capacity of the REFHYNE electrolyser installed in Germany is **less than 2% of** the country's **demand for FCR** (around 600MW), and less than 1% of the country's demand for aFRR (around 2GW in either direction)
- The following slides list key facts and techno-economic data on these four projects.
- We distinguish three different status levels of grid service provision:
- **Level 1 : ** planning to provide grid services but not prequalified by TSO yet;
- **Level 2 : ** prequalified for services by TSO, but no commercial provision;
- **Level 3 : ** commercial provision[1]

1) providing service on a regular basis to the TSO or the industrial site (in case of load balancing) and receiving remuneration from the TSO (or helping to achieve grid/imbalance fee savings in the case of load balancing)

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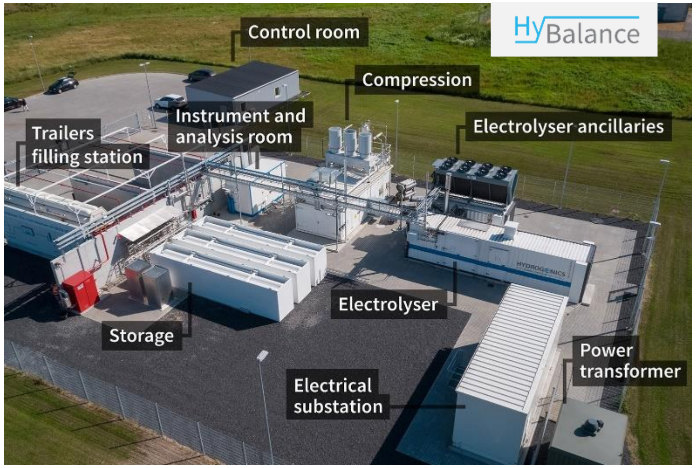
# HyBalance – 1.2 MW PEM electrolyser delivering H2 to industry and mobility

Hydrogen Mobility Europe




| Key project data[1] | |
|---|---|
| Electrolyser capacity | 1.2 MW |
| Electrolyser technology | PEM |
| Location | Hobro, Denmark |
| H2 end use | Mobility, industry |
| Project period | 2015-2020 |
| Start of operation | September 2018 |
| Project partners | Air Liquide, Cummins[1] |
| Overall budget | €15.8m |

## Project overview

- In the HyBalance project, a 1.2 MW PEM electrolyser is producing hydrogen for end uses in **mobility and industry**.
- 50% of hydrogen produced delivered via pipeline to an industrial complex.
- Other 50% delivered via tube trailers to other end uses incl. a fleet of H2 FECV taxis in Copenhagen
- 120t H2 delivered by September 2020
- Learnings of project applied to 20MW PEM electrolyser installed by Cummins at Air Liquide plant in Bécancour (Canada)

## Grid services

- Electrolyser has demonstrated a **ramp up and ramp down** time of **less than 10s** where requirements of the grid operator range between 15 to 30s[2]
- Electrolyser able to ramp up and down flexibly between **10% and 100% of nominal power**[2]
- The facility has been **approved** by the Danish energy authorities to participate in **all electricity markets**, including the Danish **FCR, aFRR, mFRR** markets[4]
- **Status: level 3**, pre-qualified and contributing to balancing the Danish electricity grid[5]

1) Further partners: Copenhagen Hydrogen Network, NEAS Energy, Ludwig Boelkow (EU Commission, 2020 a) 2) HyBalance, 2020 a; 3) FuelCellsWorks, 2020; 4) Ramboll, 2019; 5) HyBalance, 2020 b, Air Liquide 2020

# H2Future – a 6 MW PEM electrolyser providing H2 to steel plant

Hydrogen Mobility Europe


**Key project data[1]**

| | |
|---|---|
| Electrolyser capacity | 6 MW |
| Electrolyser technology | PEM |
| Location | Linz, Austria |
| H2 end use | Steel industry |
| Project period | 2017-2021 |
| Start of operation | November 2019 |
| Project partners | Voelstalpine, Siemens, Verbund[2] |
| Overall budget | €17.9m |

**Project overview**

- H2 currently used in specific applications in steel industry (e.g. annealing of cold rolled steel strips)[1]
- H2 could furthermore play major role in a potential decarbonization route of steel making (direct reduction followed by melting in electric arc furnace (EAF))[1]
- Project investigates **electrolyser capabilities to provide load balancing and grid services**
- Several pilot phases to test different use cases, followed by **quasi-commercial phase** (Nov 2020 – Dec 2021)[3]
- Project only required to reach 3,000 full load hours[3] in quasi commercial phase (corr. to load factor below 30%), thus **high flexibility** of electrolyser

**Grid services**

- Testing how electrolyser can be used for **load balancing** at the **existing plant** as well as at a potential **future** low carbon steel **plant** with EAF
- Quasicommercial phase focuses on **day ahead market and FCR and aFRR** grid services[3]
- **Status: level 3**, providing services to TSO on a commercial basis[3]

1) EU Com, 2020 b; 2) Further partners: APG (Austrian TSO), K1-Met, TNO; 3) H2Future, 2021

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# H2Future: prequalified for balancing by TSO and able to balance internal loads


- Five test phases run in 2020, starting in March 2020; followed by quasi-commercial operation period from end of October 2020 until end of 2021
- Only first results shared so far, but the project reported that the tests confirmed electrolyser is **able to provide internal load balancing**[1]
- Electrolyser has furthermore been **prequalified for FCR (+-1 MW), aFRR (+-4 MW), and mFRR**[2]
- mFRR is considered to be less relevant due to less attractive revenue in this market in Austria[2]
- In quasi-commercial phase electrolyser follows **optimized schedule acc. to Day Ahead (DA) power prices** and **participates in FCR and aFRR markets** (cp. above graph showing modelled operation)[2]
- Electrolyser finalizes schedule optimization based on forecast of DA prices **two days before real time** and decides whether to participate in FCR, positive aFRR, or negative aFRR auction
- On the day ahead it participates first in the FCR or aFRR auction, then in the DA auction[3]

1) Verbund, 2020; 2) H2Future, 2021; 3) Gate closure time (GTC) of different markets in Austria: FCR: 8:00; aFRR: 9:00; DA: 12:00

# REFHYNE: a 10 MW PEM electrolyser providing H2 to a refinery

Hydrogen Mobility Europe


| Key project data[1] | |
|---|---|
| Electrolyser capacity | 10 MW |
| Electrolyser technology | PEM |
| Location | Wesseling, Germany |
| H2 end use | Refining |
| Project period | 2018-2022 |
| Start of operation | First half of 2021 |
| Project partners | Shell, ITM, SINTEF, Sphera, Element Energy |
| Overall budget | €19.8m |

**Project overview**

- 10MW PEM electrolyser installed at Rheinland refinery in Wesseling, Germany, operated by Shell.
- One of the largest installed PEM electrolysers in the world.
- Electrolyser will provide approximately1,300t H2 per year[2] to the refinery's H2 pipeline system, currently supplied by two steam methane reformers (SMR)

**Grid services**

- Project aims to prove the electrolyser can access revenues from Germany's **FCR and aFRR** markets[3], run by the German TSOs
- Refinery also has onsite electricity generation and the electrolyser will be used to help **balance** the site's **internal electricity grid**.
- Aim to **increase full load hours** of site to achieve regular consumption from grid and subsequent grid fee reduction (see slide 17).
- This type of load balancing is likely to require running electrolyser at a **high load factor**
- **Status: level 1**, not pre-qualified for service provision yet

1) EU Com, 2020 c; 2) Refhyne, 2021 a; 3) Refhyne, 2021 b

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# Demo4Grid – 4MW Alkaline electrolyser providing H2 to industry & mobility


| Key project data[1] | |
|---|---|
| Electrolyser capacity | 4 MW |
| Electrolyser technology | Pressurised Alkaline |
| Location | Völs, Austria |
| H2 end use | Mobility, food production |
| Project period | 2017-2023 |
| Start of operation | Site under construction |
| Project partners | MPreis, Sunfire[2] |
| Overall budget | €7.7m |

**Project overview**

- Hydrogen is produced to fuel part of **heavy duty transport** fleet of food producer and trader MPREIS[3]
- Hydrogen will also be used in baking ovens for **food production**[3]

**Grid services**

- Project aims to provide **FCR** and **aFRR** to Austrian TSO APG[4]
- Furthermore **congestion management** services to the TSO are identified as a potential revenue
- Service provision to DSOs to avoid network reinforcement is considered less relevant due to immaturity of markets[5]
- Construction of electrolyser building has started in August 2020[4]
- Electrolyser has not started operation yet and thus not been tested or qualified for provision of any grid services
- **Status: level 1**, not operational and not pre-qualified for services yet

1) EU Commission, 2021; 2) Sunfire: previously IHT (Sunfire, 2021), further partners: DBC, FHA, INYCOM, FEN-SYSTEMS; 3) Mpreis, 2020
4) EU Comission, 2021; 5) Demo4Grid 2019

Hydrogen Mobility Europe

# Conclusions

**Demand and markets for grid services**

- Key grid services relevant for electrolysers are **balancing services procured by the TSO** and **internal load balancing** at large industrial sites.
- Technical requirements and procurement processes of grid services are being **harmonized** across European member states but some **differences currently remain**.
- Balancing services markets are **shallow and get saturated quickly**. **Ample supply of low carbon flexibility options** such as batteries and demand side response is likely to lead to highly competitive markets in the medium term.

**Electrolyser capabilities to provide grid services**

- **Standard test protocols** have been developed in the Qualygrids project which could allow electrolysers to be prequalified in a wide range of European countries.
- **Electrolysers have the technical capabilities** to provide balancing services (FCR, aFRR, mFRR, and RR) provided they are equipped with appropriate controlling technology.
- Currently **electrolysers don't play a tangible role in grid services markets.**
- Projects in which electrolysers provide balancing services in a **commercial** setting are **only starting to emerge.**

# H2ME 2 D4.11: Assessing the current role of electrolysers in the provision of grid services

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# H2ME 2 D4.11: Assessing the current role of electrolysers in the provision of grid services

Hydrogen Mobility Europe

# Assumptions of slides 16 and 21

**Assumptions slide 16**

| Quantity | Unit | Value |
|---|---|---|
| Electrolyser CAPEX | €/kW | 1,300 |
| Electrolyser OPEX | % of CAPEX | 5 |
| Electrolyser lifetime | years | 15 |
| Interest rate | % | 4 |

Assuming electrolyser can purchase electricity at the wholesale price (cp. (Qualygrids 2019) for more detail on electricity price for electrolysers in Germany)

**Assumptions slide 21**

| Technology | Capacity (GW) | Source |
|---|---|---|
| Electrolyser | 5 | (BMWi, 2020) |
| Batteries | 10 | (Bundesnetzagentur, 2018), scenario B |
| I&C DSR | 4 | (Bundesnetzagentur, 2018), scenario B |
| EVs | 3.3 | Peak demand of 10m Evs, German govt.'s 2030 goal[1] |
| Pumped storage | 11.9 | (Bundesnetzagentur, 2018), scenario B |

Assumptions of EV peak demand calculation: 60% of EVs charge at home, 15% of those plug in in the hour of peak EV demand (early evening), home chargers have 3.7kW charging capacity;

1) (ZEIT online, 2020)

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