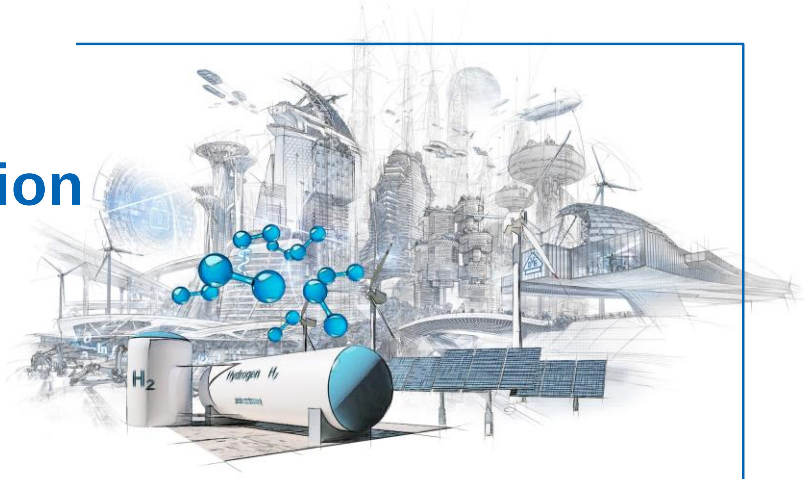
VDE Discussion Paper

Grid-serving integration of electrolysers



Flexibilization of the energy system through the use of electrolysers

The German government's goal of achieving climate neutrality by 2045 requires systemic restructuring of all parts of the economy, especially in the energy sector. The aim is to reduce Germany's energy demand by raising efficiency levels and by reducing greenhouse gas emissions practically to zero, while always guaranteeing security of supply. Therein the electricity sector plays a central role. Increasing electrification widens the sector's influence, while its emissions are decreasing through the expansion of renewable energies. In the future, the electricity sector will also indirectly supply green energy and resources to sectors that are difficult to electrify (e.g., via power-to-gas processes and their downstream products). The electricity and gas sectors currently function independently of each other in many aspects. Accordingly, the use of hydrogen will connect them more closely than before.
Ongoing energy saving measures will represent a crucial component in the transition, as well as the efficient use and storage of energy from renewables. The curtailment of fluctuating renewables in response to power grid congestion represents a widely discussed problem that is already addressed from many angles. Also in this field hydrogen can assist (BMWK, 2022; Art. 4 Abs. 4 European Commission, 2022; Netzentwicklungsplan Strom, 2022). Increasing the level of flexibility in the power grid constitutes a possible solution. Here electrolysers can provide flexibility as flexible consumers of electricity. However, the integration and operation of electrolysers in the power grid must be evaluated not only from a technical but also from an economic perspective.

This discussion paper aims to highlight and assess the opportunities and challenges presented by increasing flexibility through the integration of electrolysers. The objective of the paper is to stimulate further discussion on this topic to achieve consensus on a suitable framework in the future. For electrolyser operators it also identifies potential additional business models, enabling them to assess how these might develop further.

Abstract

Different options are available for increasing the flexibility of the power grid. Currently, there are various ways of defining these options. This discussion paper presents one such definition for the flexible use of electrolysers which brings the electricity and gas sectors closer together striving for of an optimal overall system integration. The power grid itself has its own requirements regarding flexible electricity consumption. These requirements should be considered in the technological specifications for electrolysers. To achieve this, electrolysis projects should be designed for optimal operation in terms of economic efficiency, lifetime and overall system integration. Flexible electrolysis should provide an additional source of income within the overall system-serving approach.

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How to define flexibility?

Converting the energy system to renewable sources requires new modes of operation for all energy plants. It is crucial to establish uniform definitions and terms for the use of flexibility. This avoids unequal states being compared with each other in a target system. Currently, the definitions still leave room for interpretation (Schulze et al., o. J.). This also became evident while composing the paper of this paper, with the various parties involved holding different views.[1] In the following paragraphs, the terms are defined based on a cross-system or cross-sectoral approach which does not fully correspond to present practice and should therefore be regarded merely as a basis for discussion.

Grid compatibility:
All equipment and plants connected to the power grid must act in a grid-compatible manner, i.e., they must not cause malfunctions and thus not endanger operation of the grid. The current requirements are defined in the Technical Connection Rules (TCR) for all four voltage levels - low, medium, high and extra-high voltage (§19 EnWG, 2005; VDE FNN, 2022). These are linked to the conditions of the respective grid level.[2] Grid compatibility is therefore the basic prerequisite for connecting a plant to the power grid. It includes verifying compliance with specified electrical properties and checking the fulfilment of the technical connection criteria (e.g., harmonic feedback, active and reactive power, interaction of the electrolysis power electronics).

Grid-serving operation:
Plants that reduce grid congestion and the need for grid expansion in the long term or which optimize grid operation act grid-serving (Schulze et al., 2021). The grid operators can ensure such grid-serving operation by controlling the plants. At the different voltage levels, they intervene in the power grid, depending on the situation. Grid expansion and operation costs can be reduced as a result (Schulze et al., 2021, S. 5). This primarily affects the transmission system operators, who bear responsibility for the electricity supply system (§13 EnWG, 2005). In some cases, there is a market for grid-serving behaviour, in which grid and plant operators meet (e.g. balancing power market). However, in other cases, there are no market-based but administrative procurement solutions (EnWG, 2005).

System compatibility:
Analogous to grid compatibility, plants that interact with a number of different systems or sectors (e.g., electricity, heat, gas) should meet the requirements of all the connected systems. Such a cross-system approach is currently not common practice. However, this would be essential for electrolysers, e.g., because their hydrogen feed-in should not exceed the capacity limits of the connected gas gid. If, in addition, they also fulfil the requirements of power grid-compatible operation, electrolysers are then system-compatible based on this definition.

System-serving operation:
Plants that operate grid-serving across different systems or sectors and which also integrate market actors are defined as system-serving by this paper. Their behaviour is therefore "overall system-serving". For example, in addition to offering power grid services, system-serving hydrogen production can use the feed-in to actively optimize the calorific value of the gas mix in the gas grid as required. However, distribution system operators can also initiate system-serving operating modes in plants: operation management, frequency stability, voltage stability and supply restoration.

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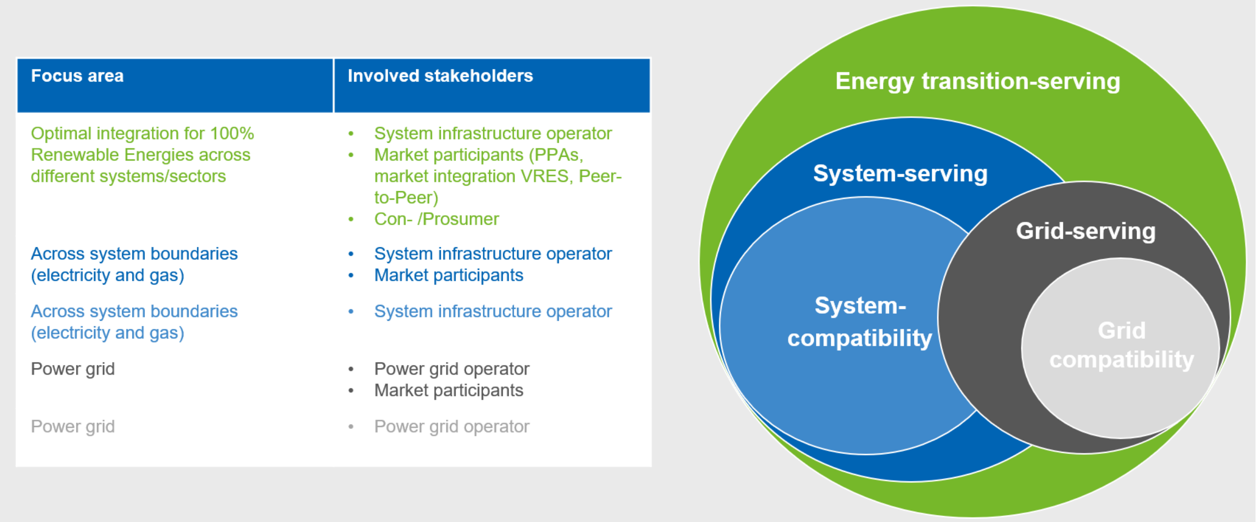
[1] In addition to the terms "grid-serving" and "system-serving" used here, the VDE ETG "Flexibilization of the Energy System" Taskforce also uses the terms "grid-oriented" and "system-oriented". Both terms refer to the electricity system and not to the overall system-supportive perspective as defined here. However, a further distinction is often made between specific local situations and bidding zones in these definitions.

[2] Information about the TCR for the medium voltage level can be found here:
https://www.vde.com/en/fnn/topics/technical-connection-rules/tcr-for-medium-voltage
General information on the TCRs can be found here. https://www.vde.com/en/fnn/topics/technical-connection-rules

Energy transition-serving operation:
The energy transition-serving operation of a plant goes beyond grid and system-serving operation in that all systems and sectors are optimised in their transformation towards an energy supply based entirely on renewable energies. Therefore, this approach considers the best possible physical and market compatible integration of variable renewable energy sources (VRES) such as wind and solar energy (Schalling et al., 2022).[3]

Figure 1 illustrates the relationship between the defined terms, their respective focus and objectives, and the actors involved. This does not, however, describe the current situation. It represents a possible target system for the optimum integration of VRES.



Focus area	Involved stakeholders
Optimal integration for 100% Renewable Energies across different systems/sectors	System infrastructure operator Market participants (PPAs, market integration VRES, Peer-to-Peer) Con- /Prosumer
Across system boundaries (electricity and gas)	System infrastructure operator Market participants
Across system boundaries (electricity and gas)	System infrastructure operator
Power grid	Power grid operator Market participants
Power grid	Power grid operator

Figure 1 Overview of the defined terms, their respective focus and their interrelationships in a possible target system, and the actors involved. (VDE chart based on information from Green Planet Energy eG)

Which electrolysis technologies are suitable for flexible operation?

The three most common electrolysis methods at present differ regarding their suitability for flexible operation. Currently, proton exchange membrane (PEM) electrolysis is establishing itself in widespread use (Hydrogen Europe, 2022). It serves as the basis for this discussion paper. Nevertheless, the other two technologies should not be disregarded, which is why they, too, are outlined. In general, it is important that all technologies offer the necessary flexibility to meet the present and future requirements of the energy system in terms of operation modes and further development of electrolysis technologies.

Alkaline electrolysis processes (based on diaphragms = AEL, or membranes = AEMEL) are among the oldest and most established high-durability electrolysis processes. However, many of the designs used to date are less well suited for load changes within seconds or for longer downtimes in intermittent operation. These are technological factors which made high-flexibility operation difficult to date. However, this technology is likely to undergo further innovation in the coming years. Advancements in novel Anion Exchange Membrane (AEMEL) technologies represent one example of the progress towards more flexible devices.

Flexible integration is most challenging in the case of **solid-oxide electrolyser cells** (SOEC, high-temperature electrolysis HTEL). This type of electrolysis makes use of a ceramic membrane, whose operation typically requires temperatures of 500°C to 850°C. (AEL and PEM operate at 40°C to 80°C.) As a result, the technology requires longer ramp-up phases after downtimes. In the medium term, however, research aims to investigate this technology’s flexibility in combination with different application scenarios

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[3] Energy transition-serving operation is based on an integrated approach that optimizes the physical and market integration of VRES in an efficient energy system in addition to being grid- and system-serving. The overarching goal is to support the energy system in its transition towards 100 % renewables. In addition, energy transition-serving approaches promote local integration (e.g., through participatory forms of ownership or increased coupling with local renewable energy production) as well as the systemic integration of the products hydrogen, oxygen and surplus heat.

to increase its compatibility (Projektträger Jülich (PTJ), 2022, S. 11 f). The potential for high efficiencies and the possibility of directly producing not only hydrogen but also other products such as syngas is promising.

PEM electrolyser technology is comparatively young but offers advantages regarding of partial and overload.[4] In addition, it can respond rapidly to load changes. These advantages are mainly based on the membrane properties, in particular the differential pressure stability and the simple periphery. In hot standby it is operational in a few seconds and allows higher load gradients than AEL. However, dynamic operation causes greater degradation of the expensive catalytic converters, thus shortening the service life. In summary, there is still significant development potential to optimize PEM electrolysers for service life in flexible operation and to further reduce acquisition costs (DLR, 2020).

Table 1 Overview of the types of electrolysis and their suitability for some flexibility markets (VDE chart based on (ENTSO-E AISBL, 2022))

Electrolyser Technology	**Response time (cold start)**[5]	**Frequency Containment Reserve (FCR)** Full Activation Time (FAT): 30 sec Min. Size: 1 MW Bid duration: 4 h	**Automatic Frequency Restoration Reserve (aFRR)** FAT: 5 min Min. Size: 1 MW Bid duration: 15 min	**Manual Frequency Restoration Reserve (mFRR)** FAT: 12,5 Min Min. Size: 1 MW Bid duration: 15 min
AEL	1 min – 10 Min	Yes – with limits	Yes - with limits	Yes
PEM	1 sec – 5 Min	Yes – with limits	Yes	Yes
SOEC	<60 Min	No	No	No

What role does the flexible integration of electrolysers play?

Decentral variable renewable energy sources (VRES) are installed on a large scale and must be integrated into the power grid. Hence, the power grid must be expanded accordingly. If grid-serving electrolysers are installed in power grid sections with a substantial surplus of renewable energy, this can help to reduce the costs of the necessary power grid expansion. This is because electricity from renewables that cannot be integrated into the power grid would be usable through electrolytic conversion into hydrogen. This grid-serving mode of operation thus increases the overall systemic utilization of the RE plants and avoids congestion in the power grid.

Another factor is the imbalance of electricity consumption and VRES at times. However, electricity generation and consumption must match at any point in time. Historically, fossil power generation has been able to adapt to consumption. In contrast, VRES-based generation now requires consumption to follow the generation as closely as possible. Electricity storage and flexibility options can help close this gap and harness surpluses of renewable energy. In the future, flexible electrolysers will gain importance for the electricity system to use not only market- but also grid-related surpluses of renewable generation.[6] Today, around five to seven terawatt hours of electricity from VRES are curtailed annually as part of grid congestion management in Germany alone (Merten et al., 2020; Schalling et al., 2022). However, such curtailment mostly occurs locally and is thus distributed over many locations. According to Merten et al – depending on the forecast scenario – the amount of surplus could increase significantly by 2030. Flexible electrolyser operation at grid sections with renewable surpluses can ensures the utilization of VRES.

As electrolysers are additional electricity consumers in the electricity system not only the location of the electrolysis plant but also the operation mode are decisive factors in determining how or whether the local power grid must be expanded. If an electrolyser is operated as a static load in order to maximize its full

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[4] This particular mode of operation is currently only at the research and development stage.
[5] It should be noted that definitions of or assumptions regarding cold start-up times vary widely in the literature. (ENTSO-E AISBL, 2022, S. 10)
[6] Electrolysers need suitable gas storage facilities and gas grid connections to be able to guarantee this flexibility.

load hours for its cost-efficiency, this can also increase the need for greater local power grid expansion. (Netzentwicklungsplan Strom, 2022; Schalling et al., 2022)
In the context of the overall energy system, additional factors to grid-serving operation should be considered to balance grid and electrolysis expansion, respectively. The conversion losses of electrolysis can, for instance, make grid expansion more efficient in comparison. Moreover, a statically operated electrolyser is an additional load in the local power grid which must be supplied with electrical energy and can increase stress on the grid. The resulting higher base load can lead to higher emissions in the power grid.

Flexible operation of electrolysis can therefore help to balance the expansion of VRES and storage technologies. Beyond that, energy transition-serving operation would also ensure optimal physical and market-coordination across systems and sectors.

What opportunities and risks result for electrolysis operators from flexible operation?

For electrolysis operators, cost effectiveness is an important requirement for flexible operation. Apart from the hydrogen price the number of full load hours and the resulting electricity costs as well as the production volume of hydrogen are the key factors in this respect. Due to the currently high technology costs, the specific hydrogen production costs decrease with the number of operating hours. Longer operating hours can, however, increase the hydrogen production costs due to the increased electricity consumption during high-price hours. As already described in the section on the different electrolysis technologies, the operating mode also has an impact on the service life of the electrolyser. This may lead to, e.g., components requiring replacement or to a reduction in efficiency. In practical application, little data is currently available to accurately reflect the long-term effects of flexible operation. (Papakonstantinou et al., 2020; Van Pham et al., 2021)

The study by the Reiner Lemoine Institute (RLI) concludes that "[...] economically viable operation of electrolysers from surplus energy alone is currently not yet possible". Under current conditions, it is expected that flexible electrolysers of up to around five megawatts can be operated cost-effectively from 2030 onwards.[7] In exceptional cases of grid sections with high local VRES generation and low grid capacity, grid-serving electrolysers with 14 megawatts can also be cost effective (Schalling et al., 2022). Especially in grid sections with large shares of VRES, there is a high probability that grid-serving modes of operation will be cost effective. If a grid area is load-dominated, grid-serving operation becomes less probable due to the lack of energy surpluses.

Today, large-scale electrolysis plants have the advantage of lower investment and operating costs through economies of scale. This advantage may be reduced in the future if, as expected, the specific investment costs decrease with higher production numbers. This means that electrolysis plants in the single-digit megawatt range can become more attractive and thus contribute to decentralised supply. However, not only the cost development of electrolysers, but also the development of the market design or financial incentives are decisive for the role of electrolysers in the overall system (Müller, 2022). For instance, economic incentives for electrolysers of all sizes could encourage grid-serving operation. This would allow cost effective flexible operation of large electrolysers as well. In general, however, our electricity system should place a greater emphasis be oriented more towards on rewarding flexibilization in order to incentivize grid-serving behaviour power grid.

In addition, electrolysis operators adapt the products to the customers. It is important, e.g., to determine in advance how to manage flexible hydrogen, heat, and oxygen supply on a local level. If the demand is not compatible with the operating mode of the electrolyser, flexible operation is difficult to execute. Buffer storage (local hydrogen storage or a hydrogen network) can help alleviate this problem.

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[7] Investment costs, electricity purchase prices and location factors are important factors in estimating cost effectiveness. Therefore, it is not possible to state how many operating hours are generally needed to achieve economic viability. However, it can be assumed that an increase in VRES will lead to a corresponding rise in the full load hours of the electrolysers (Netzentwicklungsplan Strom, 2022).

Ideally, the dimension of the electrolysis project is optimally designed for all location factors of the grid interconnection points, enabling flexible and system-serving operation. It therefore depends on the local conditions and, consequently, on the business case and operational management. The prerequisite for this is that the regulatory framework supports the operational management and the sales model.

Which markets can be used to operate electrolysers flexibly and cost-effectively?

Essentially, the market price of green hydrogen and thus both the electricity purchase costs and the price development of carbon dioxide emissions (CO_2) are the decisive factors for the cost effectiveness of an electrolyser (Netzentwicklungsplan Strom, 2022; Schalling et al., 2022). As mentioned in the previous section, especially the current high fixed costs create an incentive for large numbers of full load hours. This discussion paper argues for greater consideration of flexible operation of electrolysers. After all, the flexible integration of electrolysers is already possible today, primarily with the help of three markets: the day-ahead market, the intraday market (both spot markets) and the balancing energy market.

The electricity price signals of the spot markets can be used to control the operation of the electrolysers due to the increasing temporal correlation between electricity prices and the RE shares in the power grid and associated carbon emissions of the electricity mix. Here, low prices are an indication of a relatively high share of RE and relatively low carbon emissions in the electricity mix.

Apart from participating in spot markets, electrolysers can offer system services and thus additionally act in a grid-serving function. These services balance generation and consumption in the short-term by providing balancing power. As shown in Table 1, a distinction is made between the three types of balancing power (FCR, aFRR, mFRR) and between positive and negative balancing power. In the case of FCR, a symmetrical, i.e., both positive and negative, amount of power is placed as a bid on the balancing power market. In the event of a call from the grid operator, the electrolyser must be able to provide the requested power within 30 seconds and deliver it for at least 15 minutes. (See Table 1) Alternatively, the electrolyser can submit separate bids for the aFRR and mFRR in the balancing power market and then, for example, use surplus electricity from the grid in the event of oversupply. This is referred to as negative balancing power. The power must be available within 5 minutes in the case of aFRR. The balancing power is managed by the transmission system operators in an auction-type market procedure.

Ideally, the local state of the electricity grid, especially grid congestion, should also be considered to ensure flexible and grid-serving operation. This is currently not directly possible but could be implemented via grid "traffic lights" that forecast loads of local grids (Schleswig-Holstein Netz AG, n.d.). In this regard, distribution and transmission system operators will play a central role in the future.
The combination of price- and grid-based signals for operation management offers plant operators the advantage of mainly utilizing economically favourable times. Plant operators can optimize independently within the specifications of the grid connection point set by the grid operator. It is crucial that the grid operator's specifications must always take highest priority.
However, local grid requirements and market prices may differ in the bidding zone. As a result, the use of an electrolyser may relieve the stress on the local grid or even prevent VRES curtailment while simultaneously operating at high electricity prices due to a high load in the overall bidding zone. Future flexibility markets can help to avoid these local effects and create a financial incentive for grid-serving operation.

In addition to the electricity markets, electrolysers can operate in other markets and thus couple sectors. The coproducts of electrolysis – surplus heat and oxygen – can be used and marketed as well. In these forms of marketing, the fluctuations which result from flexible supply must be accommodated with the help of redundancies (e.g., in heat supply) or buffer storage to avoid limiting the flexibility potential on the electricity side.
In summary, grid-serving operation can already support the cost effectiveness of electrolysers today. However, there are still insufficient incentives for load-side flexibilities. Moreover, this source of income is highly complex due to the large number of signals that have to be processed in order to determine the respective optimal operating point of the electrolyser. More companies are implementing this (as shown in figure 2) operation mode in different forms in their portfolios.

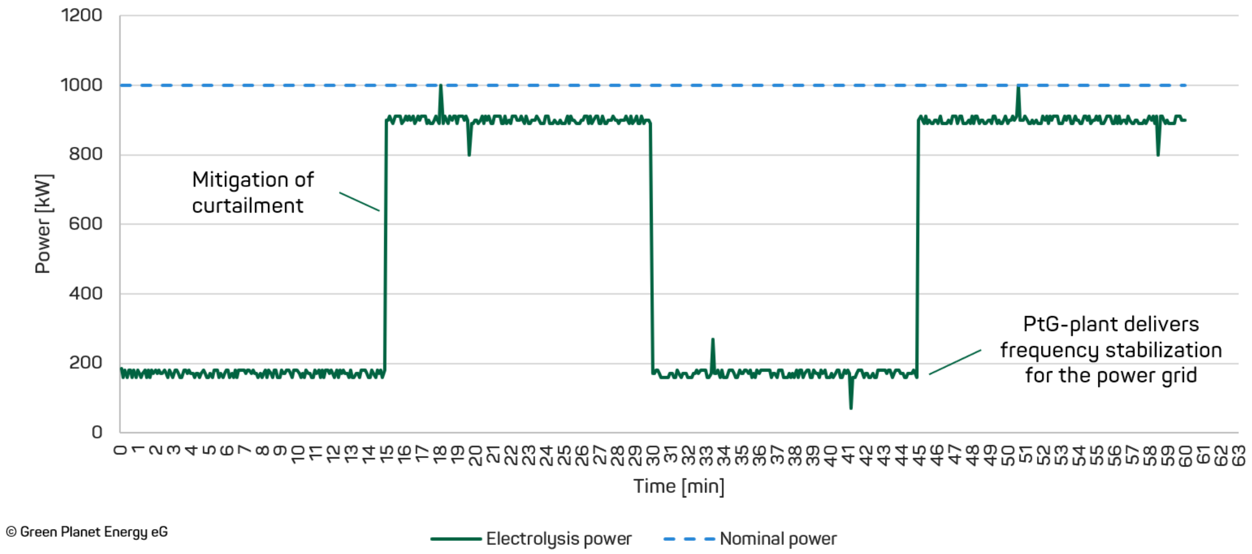

Figure 2 Example of an operation mode that takes both local grid signals and primary balancing power into consideration. (Source: Green Planet Energy eG)

A glimpse into the future – What are the requirements for integrating more electrolysers to provide flexibility in Germany?

Currently, 65 megawatts of electrolysis capacity are connected to the grid in Germany (E.ON, 2022). According to the Federal Government's targets as set out in the 2021 Coalition Agreement, ten gigawatts are planned by 2030 (Koalitionsvertrag Regierungsparteien, 2021, S. 60). Flexible integration is a key component in both the Federal Government's energy policy package of April 2022 (“Easter Package”) as well as in the RED II of the EU (Renewable Energy Directive) (BMWK, 2022; European Commission, 2022). By the time the discussion paper was published, the criteria on additionality, temporal geographical correlation with RE production and certification of hydrogen from surplus electricity were not fixed. This led to uncertainty in the management of flexible integration (European Commission, 2022; European Parliament, 2018).

High technology costs currently provide an incentive for high full load hours. To avoid an additional base load caused by inflexible operation (ten gigawatts as currently targeted), however, it is important to consider and incentivize flexible integration of this local demand already today. The German grid development plan for 2037 considers suitable electrolysis sites in terms of the electricity and gas grids (Netzentwicklungsplan Strom, 2022). Yet, corresponding allocation signals for investment and flexible operation are still missing. Some pioneer projects are already using flexible operation as an additional source of income for their electrolyser.[8]

This discussion paper shows that there are some technical possibilities but limited economic incentives for flexible integration of electrolysers into the power grid. The local energy demand and availability of VRES make the location issue decisive in determining the cost efficiency for the flexible operation of electrolysers. Furthermore, the development of technology costs as well as price developments of electricity, hydrogen, surplus heat and oxygen are essential to the cost efficiency of electrolysers.

The different types of balancing power react to short-term discrepancies between consumption and generation. Electrolysers can help here, but they are in competition with other technologies (e.g., battery storage). Overall, however, our electricity system should focus more on incentivising flexibility in order to stimulate grid-serving behaviour in the power grid. Electrolysers currently pose a challenge for grid operators confronted with grid congestion and the resulting need for grid expansion. Clear incentives and

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[8] Examples include the Windgas Haßfurt project for the use of local RE surpluses, and the Windgas Haurup project for preventing curtailments of wind power. The Mainz Energy Park and Wunsiedel projects have also integrated the flexible operation of electrolysers into their concepts.

regulations to promote grid-serving operation are necessary to ensure the efficient integration of electrolysers.
Uniform definitions are another prerequisite for effective overall system integration. The areas in which standards are necessary have yet to be determined. The writing process of the discussion paper has highlighted how different the definitions currently still are and that the focus often does not cover the overall system-serving perspective. VDE, DKE and FNN represent ideal partners for shaping this debate.

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The Authors

- **Andrea Appel**, VDE
- **Carolin Dähling,** Green Planet Energy eG
- **Christoph Heinemann,** Öko-Institut
- **Florian Lessing,** VDE Renewables
- **Friedrich Kunz**
- **Lucy Schwarz,** Uniper Hydrogen GmbH
- **Mats Bednarczyk,** Green Planet Energy eG
- **Moritz Vogl,** Öko-Institut
- **Phillip Miersch,** VDE FNN
- **Sebastian Kosslers**, VDE DKE
- **Thomas Holzmann,** VDE