Readiness level of technologies for the "Energiewende": Results from VGB Scientific Advisory Board study
Technologie-Reifegrad von technischen Prozessen der „Energiewende“: Ergebnisse einer Studie des wissenschaftlichen Beirates des VGB

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Abstract

A primary objective of the German *Energiewende* is a gradual increase in usage of renewable energy to over 80 % of electricity consumption. At the same time, primary energy consumption is being reduced by 50 % of 2008 levels. 2050 is the target year. Changes to the electricity, heat and mobility sectors are expected to reduce greenhouse gas emissions by 80 % - 95 % compared with the base year of 1990.

The electricity supply plays a major role in fulfilling the above-mentioned objectives. However, the use of volatile renewable energy sources (RES) for power supply requires large-scale storage solutions. The options for direct, large-scale storage of electricity are limited. Therefore, an alternative energy supply system is needed that can buffer temporary oversupply from RES by storing it for later use. A sample structure for such a system is shown in Figure 1.

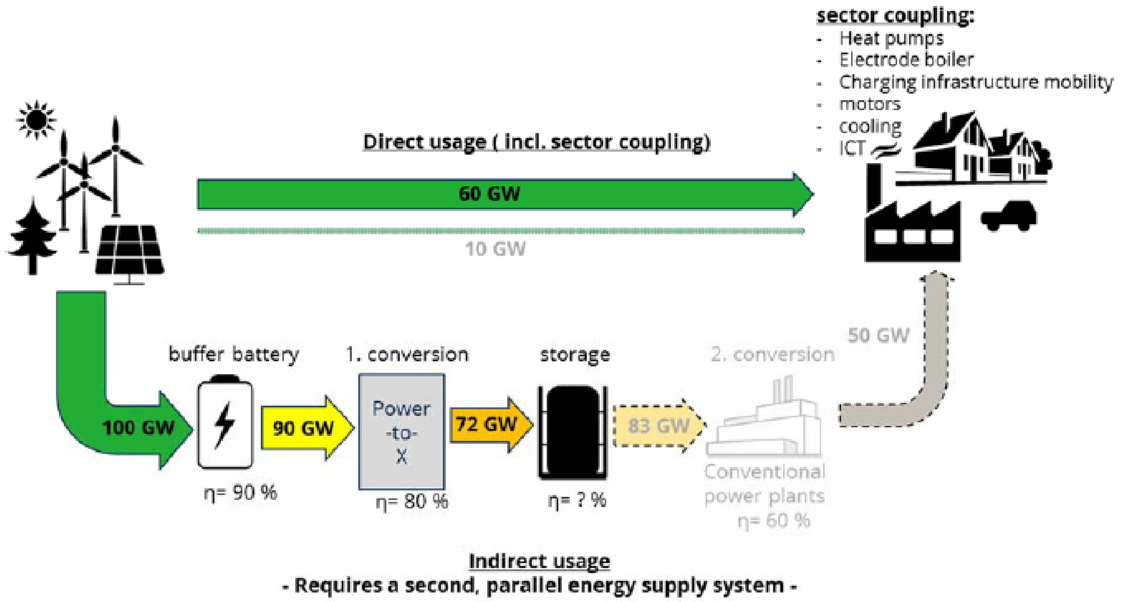


Figure 1: power supply system dominated by RES with parallel storage system (bold/filled components: sufficient RES supply with surplus; transparent/gray components: RES undersupply with compensation by stored RES energy and conventional power plants; degree of effectiveness illustrative)

In Figure 1 two possible (extreme) situations are shown. The filled components represent full supply by RES. A mean power load of 60 GWel, which includes the final energy demand for heating, cooling, electricity and mobility, is completely covered by volatile RES. Temporary surpluses are stored by means of the parallel storage system. This consists of (buffer) batteries, which reduce rapid load changes for the subsequent, sometimes slower, conversion technologies and further serve to provide electrochemical storage. Energy storage after initial conversion may be thermal, chemical or mechanical. In the event of an undersupply of electricity, stored energy has to be converted a second time to provide power. It may also be used without a second conversion e.g. for heating (gray / transparent components). In a first simplified approach, the supply of electricity is considered primarily in the context of the technology matrix depicted in Figure 2. Some of the required technologies in Figure 2 are not part of the TRA (Power-to-Mechanical, Heat-to-Power, Heat-to-Heat, Mechanical-to-Power), because of their conventional nature and mature stage of development. Further, the conversion of energy in batteries is an inherent part of the technology and thus not explicitly designated as first/second conversion.

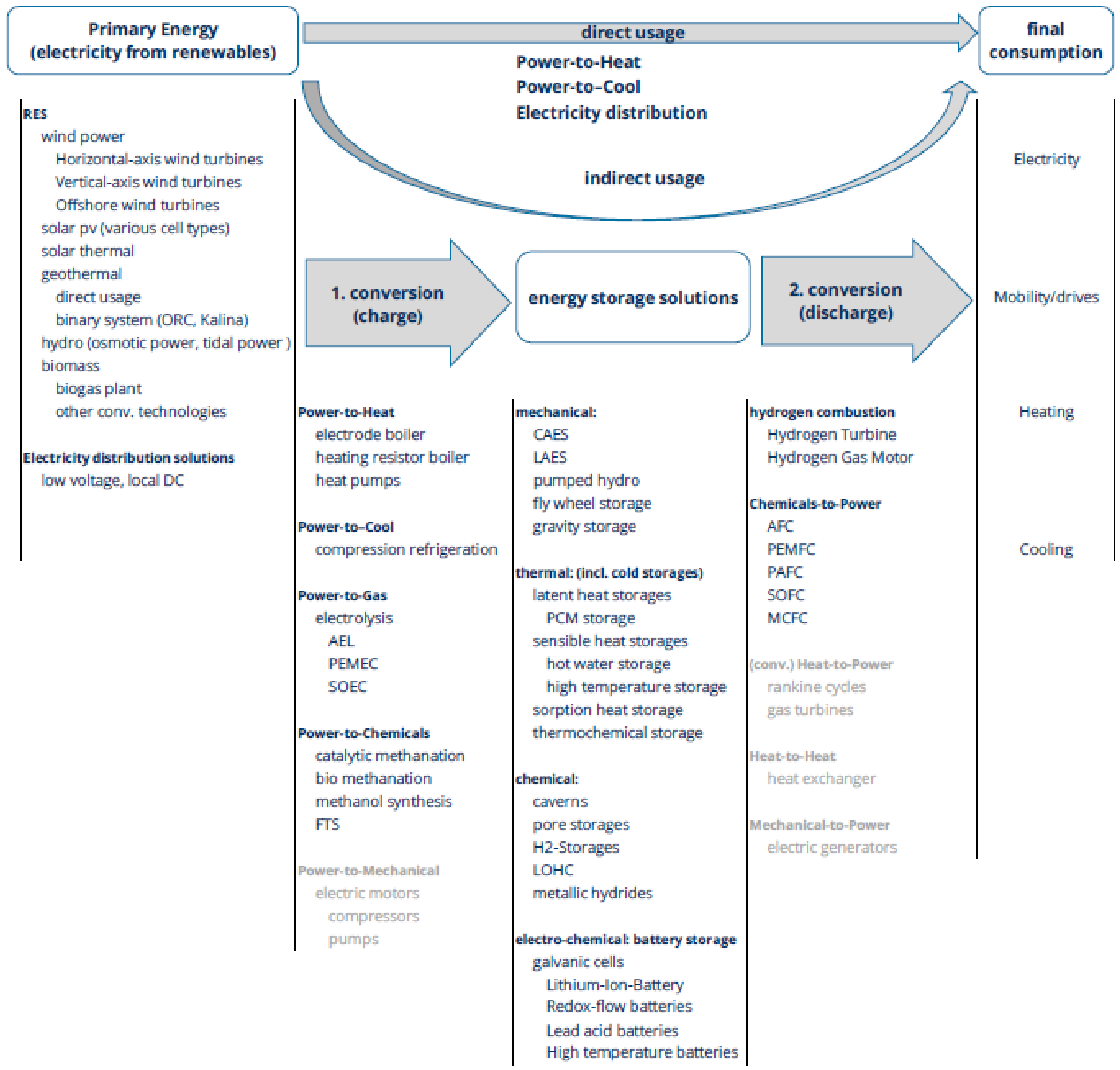


Figure 2: technology matrix

The primary goals of this research study are:

1. Systematic description and presentation of the critical technologies and components for the *Energiewende* (in relation to generation, distribution, storage, usage) – focusing on electricity,
2. Evaluation of the Technology Readiness Level (TRL) of each of the respective technologies,
3. Description of development potential – in terms of technology and capacity,
4. Identification of development deficits in the respective technologies.

The specific approach summarized in Figure 3 was therefore chosen. Basic assessment in line with the principles of DIN ISO 16290 is supported by several interviews with a range of experts and then reviewed for each technology.

Figure 3: approach of the study

Each chapter is structured the same way according to the template set out in Figure 4:

Technology description

- A basic overview of the respective technology is given (state-of-the-art)
- physical basics are shown
- Relevant techniques and critical components are shown

Potentials a) Technical development potential

- Focusses on the critical components
- Shows current developments and projects for improvement

Potentials b) capacity potential in Germany

- Gives an estimation of the capacity that could be installed in Germany or would be necessary for a certain purpose (e.g. maximum wind energy onshore; power-to-heat potential from heat pumps for base load in district heating)

Current status in Germany

- Describes current facilities and key indicators in Germany (rated capacities for power, load hours, energy supply etc.)

TRL Assessment

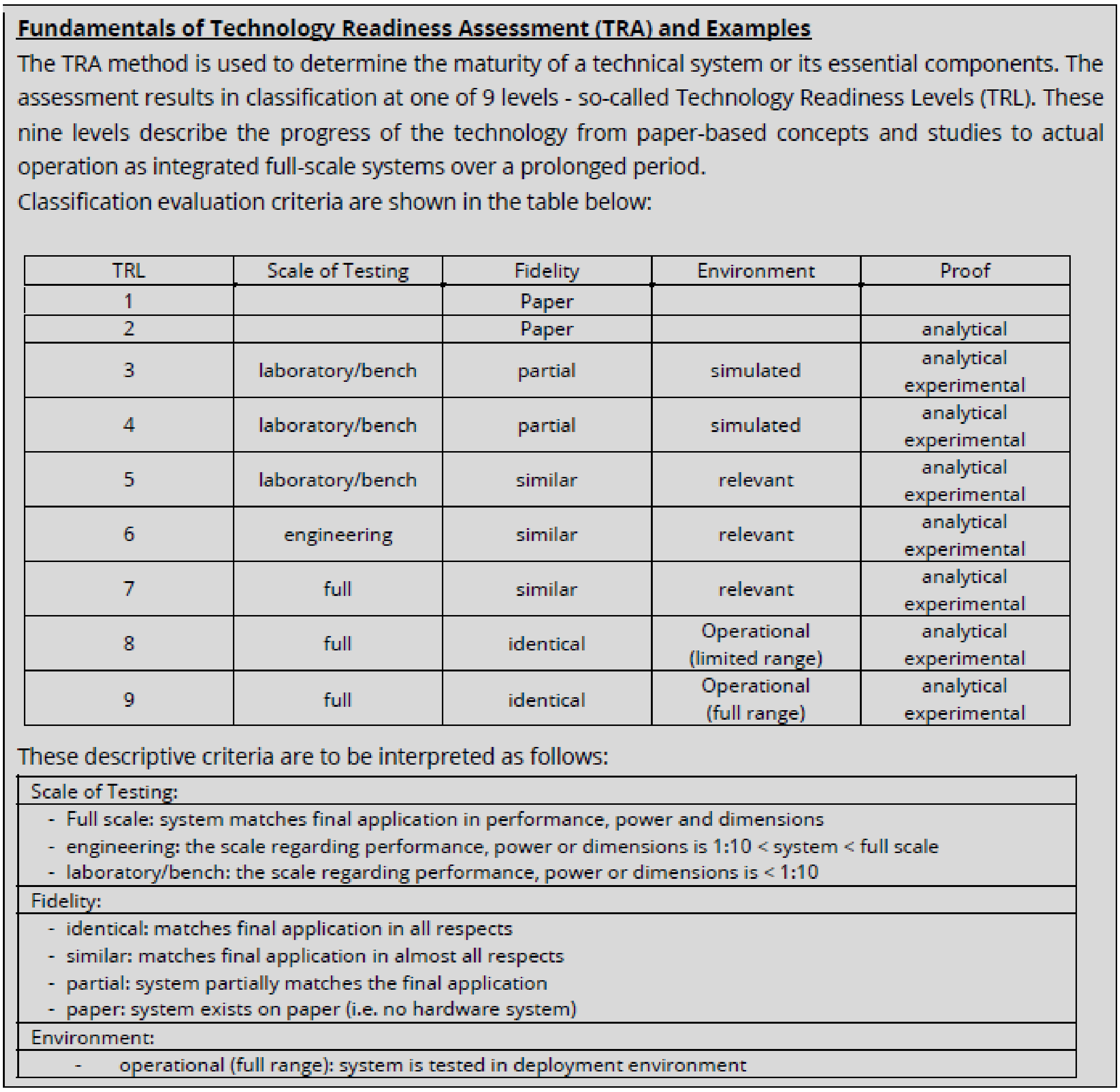
- Summary of the findings from section potentials and currents status
- Resulting in a table with TRLs for presented techniques or critical components

Figure 4: chapter structure for each technology

Important though it is to state what is in the study, it is also important to indicate what is not included:

- The focus is on electricity and its usage in Germany. Technologies primarily used for e.g. heating (solar heating) or mobility (fuel from biomass) are therefore excluded.
- The study focuses on new or recent technologies. Mature and conventional technologies such as gas turbines, steam turbines, pumps, electric motors, generators, el. Transformers etc. are thus excluded (grey in Figure 2).
- A TRL 9 does not mean that all aspects of a technology are fully developed, e.g. although technologies for using hydropower as primary renewable source of energy are well advanced, approaches to further improve water turbines and the complementary systems (flow control, generators etc.) are less so. These improvements are indicated where possible, but they do not affect the readiness level.
- Economic and ecological issues are also excluded. For all technologies with TRL 6-9, one of the major goals for further development is improvement of scalability by means of, and in order to achieve, cost degression.
- The importance of smart grid components like smart controllers, smart meters and so on is beyond question. However, smart grids are a great example of a technology to which the main obstacle is not the underlying electronic parts (most electronic components are TRL 9 and commercially available) but such parts' smart interconnection and programming. System integration needs more time to develop, but that is not as a result of the components' TRL.

The study first analyzes primary energy supply by renewable energies. Special emphasis is placed on technologies and their potential including in the context of significant technological improvements and their potential for expansion (in Germany). The subsequent step analyzes initial conversion –transformation into other forms of energy that are more suitable for storage. Then come the storage solutions themselves and finally, an examination of second conversion back to electricity. The second conversion step has a strong focus on hydrogen technologies for a simple reason: the transformation of (fossil) chemical energy into thermal, mechanical and electrical power is generally established. More recent technologies, such as the Organic Rankine Cycle, have already been looked at by the primary energy sector in relation to geothermal power, thus this is not revisited e.g. for discharge of thermal storage.



Fundamentals of Technology Readiness Assessment (TRA) and Examples

The TRA method is used to determine the maturity of a technical system or its essential components. The assessment results in classification at one of 9 levels - so-called Technology Readiness Levels (TRL). These nine levels describe the progress of the technology from paper-based concepts and studies to actual operation as integrated full-scale systems over a prolonged period.

Classification evaluation criteria are shown in the table below:

TRL	Scale of Testing	Fidelity	Environment	Proof
1		Paper		
2		Paper		analytical
3	laboratory/bench	partial	simulated	analytical experimental
4	laboratory/bench	partial	simulated	analytical experimental
5	laboratory/bench	similar	relevant	analytical experimental
6	engineering	similar	relevant	analytical experimental
7	full	similar	relevant	analytical experimental
8	full	identical	Operational (limited range)	analytical experimental
9	full	identical	Operational (full range)	analytical experimental

These descriptive criteria are to be interpreted as follows:

Scale of Testing:

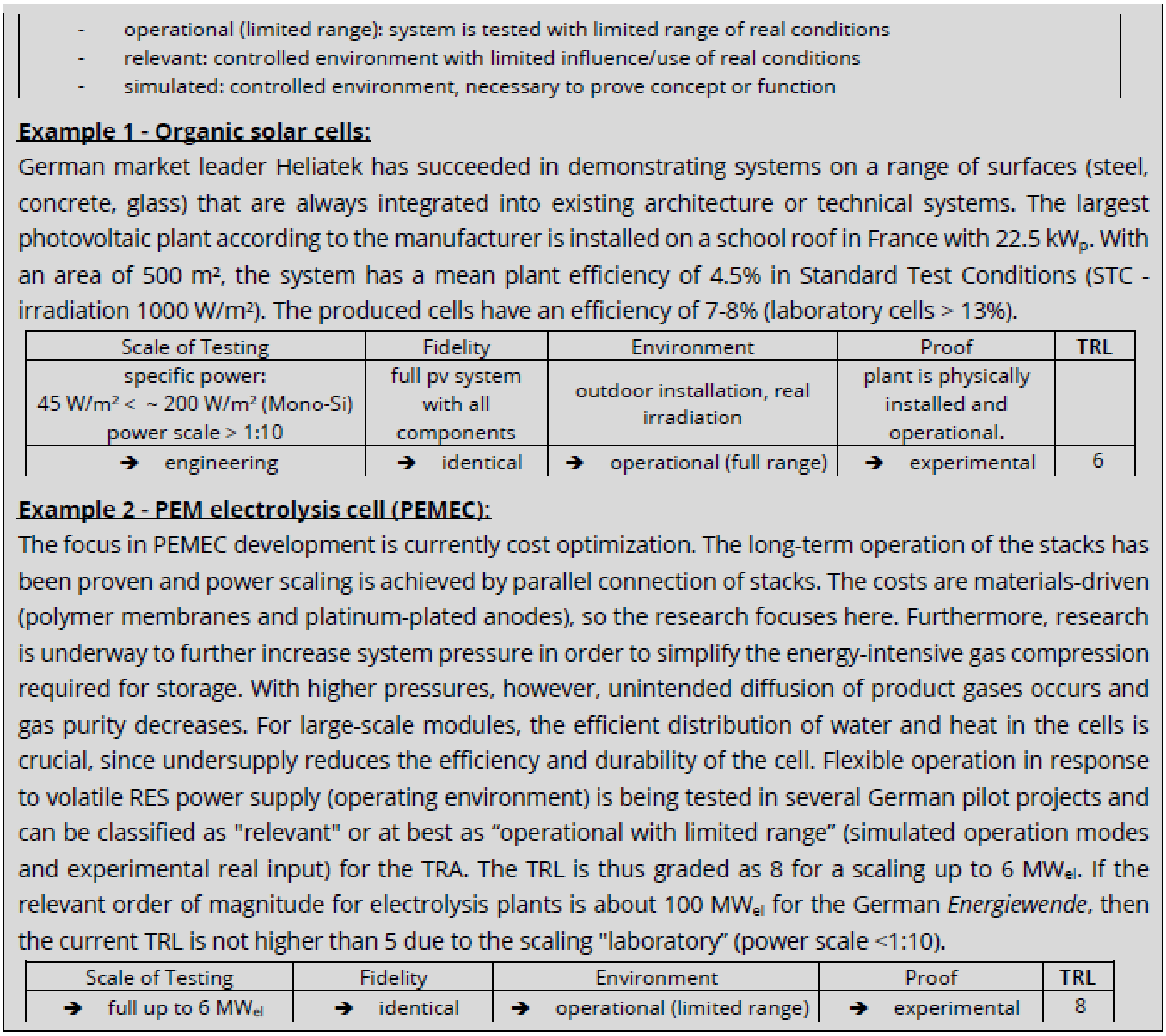
- Full scale: system matches final application in performance, power and dimensions
- engineering: the scale regarding performance, power or dimensions is 1:10 < system < full scale
- laboratory/bench: the scale regarding performance, power or dimensions is < 1:10

Fidelity:

- identical: matches final application in all respects
- similar: matches final application in almost all respects
- partial: system partially matches the final application
- paper: system exists on paper (i.e. no hardware system)

Environment:

- operational (full range): system is tested in deployment environment



- operational (limited range): system is tested with limited range of real conditions
- relevant: controlled environment with limited influence/use of real conditions
- simulated: controlled environment, necessary to prove concept or function

Example 1 - Organic solar cells:

German market leader Heliatek has succeeded in demonstrating systems on a range of surfaces (steel, concrete, glass) that are always integrated into existing architecture or technical systems. The largest photovoltaic plant according to the manufacturer is installed on a school roof in France with 22.5 kW_p. With an area of 500 m², the system has a mean plant efficiency of 4.5% in Standard Test Conditions (STC - irradiation 1000 W/m²). The produced cells have an efficiency of 7-8% (laboratory cells > 13%).

Scale of Testing	Fidelity	Environment	Proof	TRL
specific power: 45 W/m² < ~ 200 W/m² (Mono-Si) power scale > 1:10	full pv system with all components	outdoor installation, real irradiation	plant is physically installed and operational.	
➔ engineering	➔ identical	➔ operational (full range)	➔ experimental	6

Example 2 - PEM electrolysis cell (PEMEC):

The focus in PEMEC development is currently cost optimization. The long-term operation of the stacks has been proven and power scaling is achieved by parallel connection of stacks. The costs are materials-driven (polymer membranes and platinum-plated anodes), so the research focuses here. Furthermore, research is underway to further increase system pressure in order to simplify the energy-intensive gas compression required for storage. With higher pressures, however, unintended diffusion of product gases occurs and gas purity decreases. For large-scale modules, the efficient distribution of water and heat in the cells is crucial, since undersupply reduces the efficiency and durability of the cell. Flexible operation in response to volatile RES power supply (operating environment) is being tested in several German pilot projects and can be classified as "relevant" or at best as “operational with limited range” (simulated operation modes and experimental real input) for the TRA. The TRL is thus graded as 8 for a scaling up to 6 MW_{el}. If the relevant order of magnitude for electrolysis plants is about 100 MW_{el} for the German *Energiewende*, then the current TRL is not higher than 5 due to the scaling "laboratory" (power scale <1:10).

Scale of Testing	Fidelity	Environment	Proof	TRL
➔ full up to 6 MW_{el}	➔ identical	➔ operational (limited range)	➔ experimental	8

The maturity of the different technologies is highly heterogeneous across the different areas. There are high TRLs for biomass conversion in combined heat and power applications. The same applies to hydropower and electricity distribution. Despite their maturity, technologies can always be further optimized. These optimization measures are aimed at expanding life cycles or reducing costs. In other areas, such as the geothermal energy, wind power or photovoltaic (pv) power, there is still the potential for technological development which enables existing plants to be made larger or more efficient. The shortcomings of offshore wind power relate to the need for foundations in deep water and grid connection over long distances, while onshore wind power plants are mainly limited by the weight of the nacelle and the transportability of parts. In geothermal power the main components of the power train are mature, have proven themselves in continuous operation and are used worldwide, but other complementary fields lag behind. Here, the challenge lies in the exploration and drilling of suitable geothermal sources. However, this does not represent a central problem with the energy technology itself.

The initial conversion stage also includes many mature power-to-heat and power-to-cool technologies. Most of them have a capacity up to several MWel. The development of heat pumps has also improved recently: they run more efficiently, on a larger scale and at higher temperatures (>130 °C TRL 4-6). A major drawback is the ongoing low flow temperature for industrial applications. New refrigerants are still in R&D while CO2 seems to be usable but necessitates larger compression units and requires pilot scale plants to gain experience. Using combined heat pumps for cooling and heating extends energy efficiency even further but can rarely be implemented. Power-to-cool technologies are still dominated by compression cooling. The drawbacks of absorption/adsorption cooling technologies are low thermal efficiency and the large size of the systems concerned. Power-to-gas and power-to-chemicals are closely linked by the hydrogen both produce from electrolysis. The maturity of chemical pathways to convert syngas (mixture of CO, H2, CO2) to fuels via methanol or Fischer-Tropsch-synthesis is undisputed when using steam reforming and natural gas. Large-scale water electrolysis has even been used in the past to produce fertilizer. The challenge of today's electrolysers is (cost-)efficiency and durability in the context of dynamic and intermittent operation. Further shortcomings in hydrogen upgrade to methane relate to low catalytic reactor availability, while biologic methanation is still in R&D and the appropriate reaction and environmental conditions for the microorganisms are being examined.

Storage solutions have been the subject of numerous research projects and offer a wide range of options. Mechanical storage methods present a bottleneck with their low energy density, which results in large land usage. New approaches try to either "hide" the problem underground (underground water storage) or remedy the storage density problem by lifting heavy rocks. The technology underlying water pumps and turbines is mature. The concepts themselves only reach TRL 2 since none of them have been built (mostly for economic and regulatory reasons). Compressed air energy storage solutions face similar problems. In addition, they are more complex and require high temperature thermal storage for adiabatic operation, which are not available in the required MW-scale. For thermal power, sensible storage solutions based on water and gravel dominate amongst the mature approaches. Higher storage densities (and temperatures) can be achieved with latent or thermo-chemical storage (TRL 3-6), but most of them are still in R&D (= max. TRL 4) and research continues to focus on new, cheap, durable and available materials. The comparative simplicity of water and gravel are hard to overcome. Chemical storage methods also have a strong focus on hydrogen due to the abundant experience in transportation and storage of (fossil) gases, fluids and solids (TRL 9). The hydrogen tolerance of existing storage components is still in question and there are only a few demonstration units for large-scale underground storage solutions (TRL 8). The same applies to transportation technologies such as metal hydrides, LOHC, liquid hydrogen or adsorption materials (TRL 4-6). Although there have been numerous research projects, particularly in the automotive sector, the main drawback is the thermal management of these technologies. Discharging requires temperatures at the range of 200 °C which are difficult to provide in the context of highly intermittent and flexible operation. In the field of electrochemical storage, there are also mature, large-scale, proven battery types (leadacid, high temperature NaS, lithium-ion). Their weak point is their scalability. Even redox flow batteries that might overcome this hurdle are only available up to 1 MWel (TRL 9). If battery storage capacity in the magnitude of GW (or at least > 100 MW per module or system) is needed for the *Energiewende*, no battery type reaches TRL > 6. However, the widespread use of battery electric vehicles and several projects around the world demonstrate a TRL 9 for scale-ups to several MWel.

In the second conversion stage, both global research efforts and the present study are dominated by fuel cells for the reasons set out above. In this last stage, end use is more important than the maturity of fuel cell types. While PEMFCs are produced in large quantities up to 100 kWel to provide the power train for fuel cell vehicles, there are far fewer PAFCs, MCFCs and SOFCs for large-scale stationary operations in the MW-class (TRL < 7). However, over 200,000 PEMFCs and SOFCs are shipped in Japan under the ene-farm-project for small-scale home applications in the kW-class (TRL 9). The remaining drawbacks are the longevity of the cells in unfavorable conditions (gas purity) and the general high costs for large-scale stacks (based on materials and production).

An alternative approach is the use of hydrogen in conventional power technologies such as gas turbines and gas motors. Internal combustion engines can be basically adapted to use hydrogen (TRL 8). However, recent research on this topic is scarce and interest has dropped over the last decade with the technological progress made by fuel cells. With regard to large-scale gas turbines, the greatest progress has been made with non-premixed burners for syngas operation in conjunction with IGCC (TRL 8). For premixed burners the possible hydrogen fraction in hydrogenenriched natural gas has been increased to about 30 %. The main problems remaining in this field are high flame velocity (complicating flame stability and causing flashbacks) and high temperatures when burning hydrogen, causing NOX emissions without lean-burn technologies. The injection of water to lower temperatures during combustion and therefore lower NOX emissions is being investigated.

In summary, the TRL of the different systems examined varies widely. For every step in the direct or indirect usage of renewable intermittent energy sources, technologies are available that are commercially available in the MW-scale. However, RESs potentially provide power in the GW-scale. Thus, conversion technologies and energy storage systems also have to be available in the GWscale. Since the scale of testing is an essential criterion in technology readiness assessment, it reduces the TRL of essential technologies such as battery storage and power-to-gas conversion significantly. A further bottleneck is the intermittent power supply and thus operation of the technologies. Comparatively slow and thermally inert processes (e.g. power-to-gas/chemicals) are more suitable for continuous operation. Therefore, the environment criterion has to be assessed as "relevant" or "operational with limited range" and thus limits the TRLs.

Another bottleneck is the restricted availability of RESs and their dependence on natural conditions. Germany has long periods with high temperatures (reducing the efficiency of solar pv modules) or low radiation combined with poor wind conditions. In these cases, even large wind and pv capacity provide low power outputs. Those conditions pose a threat to the energy supply system, which has to be countered by large-scale (GW) conversion and storage capacity. Such capacity cannot be installed on a short-term basis and therefore requires conventional power supply technologies to bridge the gap towards a RES-dominated energy supply system. The study shows that there are significant bottlenecks in terms of security of supply.

Although the conversion of solar and wind energy into electrical energy has a very high TRL and is also highly scalable (land use, environmental impact and costs are neglected here), the intermittent availability of wind and solar energy is a natural bottleneck and requires storage solutions and backup systems. Of course, sector coupling may contribute to security of supply, but storage solutions on a GW and/or TWh scale are essential. Their TRL and scalability are still considered to be low, so that at least a decade of further development will be required to reach TRL 9. At that point nationwide implementation can begin, which in turn will take several decades to complete.