“Assessment of the Potential, the Actors and Relevant Business Cases for Large Scale and Long Term Storage of Renewable Electricity by Hydrogen Underground Storage in Europe”

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R E P O R T

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Contents

List of abbreviations

ACAES	Adiabatic CAES
BEV	Battery Electric Vehicle
BVES	German Energy Storage Association
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DOE	Department of Energy
DSM	Demand Side Management
EASE	European Association for Storage of Energy
EC	European Commission
EERA	European Energy Research Alliance
ESA	Electricity Storage Association
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHG	Green House Gas (es)
GT	Gas Turbine
GW	Giga watt
GWh	Gigawatt-hour
H_2	Hydrogen
ICAES	Isothermal CAES
km	kilometre
kW	kilowatt
kWh	kilowatt-hour

LA	Lead Acid
LCC	Last Cemented Casing
Li-ion	Lithium ion
LTA-CAES	Low-Temperature CAES
min	minute
ms	millisecond
MW	Megawatt
MWh	Megawatt-hour
NAS	Sodium Sulphur
PHES	Pumped Hydro Energy Storage
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaics
R&D	Research and Development
RCS	Regulations, Codes and Standards
RES	Renewable Energy Sources
SNG	Synthetic Natural Gas
SSM	Supply Side Management
TES	Thermal Energy Storage
TSO	Transport System Operator
TWh	Terawatt-hour
TYNDP	Ten Year Network Development Plan
UK	United Kingdom
V2G	Vehicle-to-Grid
vol.%	Volume percent
WP	Work Package

1 Objectives of the report

A first objective of this deliverable is to outline the European perspective on energy storage needs under consideration of the major European policy goals (energy diversity, GHG mitigation and industry support). The focus is specifically on electricity storage in the context of the countries' legal obligations to implement the Renewable Energy Directive and the urgently needed renewable energy build-out.

A second objective of this deliverable is to understand the potential role of hydrogen underground storage compared to other large scale energy / electricity storage concepts such as:

- compressed air energy storage (CAES),
- advanced CAES (ACAES),
- pumped hydro energy storage (PHES),
- storage of methanised hydrogen / storage of synthetic natural gas (SNG),
- hydrogen mixed-in with natural gas or other chemicals (methanol) and,
- large scale battery storage

as well as other grid based structural measures:

- grid modernization (i.e. smart grids) and
- grid management (DSM, SSM)

under consideration of energy / electricity storage needs and process performance (efficiency) and economy.

The main objective of WP2 is to document the current state of learning on the benchmarking of large scale long term hydrogen underground energy storage against other complementary and/or competing concepts to allow high penetration of renewable electricity.

2 Technical assessment of storage technologies

2.1 *European energy framework*

2.1.1 Europe's future energy supply structures

Nowadays, the EU energy generation system and energy mix is highly dependent on fossil fuels, and only nearly 45% of European electricity generation is based on low carbon energy sources, mainly nuclear and hydropower (see annex 5.1). In 2010, EU energy dependency from imported energy resources reached about 53%, increasing since 1995 (43%) [EUEF 2012]. "Global energy markets are becoming tighter and the EU security of energy supply is at risk to become the world's largest energy importer" [ES2020 2010]. "Problems with energy markets are not a new problem, as the EU internal energy markets still comprise many barriers to open and fair competition" [ECESI 2010]. Implementation of internal energy market legislation and a new energy structure are needed to advance in the EU economically and in energy terms.

"Energy infrastructure priorities for 2020 and beyond also address a new energy infrastructure policy. Electricity grids must be upgraded and modernized to meet increasing demand due to a major shift in the overall energy value chain and mix, but also because of the growing number of applications and technologies relying on electricity as an energy source, specifically to transport and balance electricity generated from renewable sources" [EIP 2010]. On medium term (2020) the development of electricity corridors is seen as a priority to ensure timely integration of renewable generation capacities in northern and southern Europe and further European integration. Gas and oil corridors are also a priority [EIP 2010] (see annex 5.2). Other medium term priorities in Europe's future energy supply structures considered are to roll-out smart grid technologies by providing the necessary framework and to develop energy storage solutions as these can compensate for intermittency of electricity and reduce the need for renewable energy curtailment [AEUES 2011].

The latter priority concerns the aim of the HyUnder project. In addition, further projects have been funded by the EC in order to encourage improvements in energy storage (e.g. http://www.store-project.eu).

On long term (2050 horizon) the EU proposes a decarbonized electricity system supported by new high-voltage long distance transmission systems and new electricity storage. This vision is presented as part of the "Energy Roadmap 2050" by the EU [ER2050 2011], [EIP 2010]. The aim of the Energy Roadmap 2050 is a new energy model based on energy saving strategies and improved management of energy demand. A key objective is a significant switch to an increased utilisation of member states' own renewable energy sources, the development of energy storage technologies and to additional electrical capacity. "To reach this objective it seems crucial to invest in R&D for the development of RES like tidal power, solar thermoelectric power, offshore wind power, biofuels and improvements in PV panels' efficiency" [ER2050 2011].

According to the Energy Roadmap 2050 ambition, natural gas will play an important role in the transition from fossil fuels to RES. The substitution of coal and oil with natural gas in the short and medium term could reduce emissions based on existing technologies with a perspective of 2030 to 2035. The demand of natural gas will be reduced in the residential sector because of the improvements in residential energy savings. Furthermore, the demand for natural gas will increase in the power sector until 2050 whenever carbon capture and storage (CCS) will be available. CCS proponents assume that technology can be introduced at large scale by 2030. Without CCS, the long term role of natural gas may be limited to a flexible backup and balancing capacity when renewable energy supplies are not available. Nuclear energy is presented as a regionally important contributor to low system cost and as one principal low-carbon generation technology nowadays and in a midterm. Since the accident in Fukushima different opinions have arisen between Member States. The Commission will continue to further increase nuclear safety and its security framework, still believing in nuclear energy playing a key role for a decarbonized energy mix in 2050. The current discussion around nuclear energy could change its perception as a low cost system. However, taking into account additional safety measures, external insurance costs and decommissioning, nuclear energy may become more expensive than other technologies.

Concerning the transport sector, e-mobility, especially focused on fuel cells and hydrogen technologies, is pointed at as the principal option, again with natural gas playing a role as transition fuel.

Analysing the EC's vision on Europe's future energy supply structures and system, the necessity to replace the old conventional fossil fuel based technologies to a new energy system based on RES becomes obvious, power generation using natural gas with CCS and nuclear power as options in some European regions. "Rethinking energy markets with new ways to manage electricity, the remuneration of capacity and flexibility on grids and pricing of carbon emissions will also be crucial" [ER2050 2011].

Concluding this section, it is found that new energy supply structures will be necessary in the medium to long term to allow a European energy system becoming less dependent on (the import of) fossil fuels and to achieve low carbon emissions. Renewable energy will need to play a crucial role in this European energy mix. In the medium term the development of energy corridors, mainly electrical corridors, and favourable policies to introduce RES will be needed to increase the share of RES in the European energy mix. In the long term a new high-voltage long distance transmission grid and new electricity storage capacities will both be needed. Natural gas based power generation with CCS and nuclear power will play a role until 2050, although after the Fukushima accident a debate among EU Member States has been kicked off concerning the sustainability and real costs of the use of nuclear energy.

2.1.2 European energy policy goals

Today energy related emissions account for almost 80% of the EU's total greenhouse gas emissions (GHG). It will take decades to steer our energy system towards a more secure and sustainable path [ES2020 2010]. The EU has been very active during the last years in the development of new energy policies with the main objective of reaching a new energy paradigm in the medium and long term, 2020 and 2050 respectively. To achieve these objectives the European Commission has implemented "Energy 2020: A strategy for competitive, sustainable and secure energy" adopted with its final version by the European Council in 2010 and the "Energy Roadmap 2050" in 2011. The central goals for the energy policy are security of supply, competitiveness and sustainability.

The Energy 2020 program establishes ambitious energy and climate change objectives:

- reduce GHG emissions by 20%, rising to 30% if the conditions are right, below 1990 levels,
- increase the share of renewable energy up to 20%,
- implement a 20% improvement in energy efficiency.

After first results and analysis of the Energy 2020 program it was estimated that only a 40% GHG emission reduction target could be reached by 2050 as compared to 1990. The necessity to establish a new energy policy goal therefore became a reality with the Energy Roadmap 2050.

The main objective of the Roadmap 2050 is the reduction of GHG emissions by 80 – 95% by 2050 compared to values of 1990. The document analyses different hypotheses to achieve these energy ambitions (see annex 5.3). In all decarbonized hypotheses significant energy savings are assumed implying a decreasing primary energy demand of 16% - 20% by 2030 and 32% - 41% by 2050. The share of RES will rise substantially in all scenarios, achieving at least a 55% share of gross final energy consumption by 2050. The share of RES in electricity provision reaches 64% in a "high energy efficiency scenario" and 97% in a "high renewable energy scenario" that includes significant electricity storage to accommodate a fluctuating RES supply even at times of low demand. Another important goal is to increase the electrical interconnection capacity between European member states by 40% by 2020.

The energy policy's success will indirectly imply reinforcement in EU industrial competitiveness by making industry more efficient. Dedicated support mechanisms should be established.

Another analysis of the EU energy supply situation and goals had been developed in 2003 (before Energy 2020 and Roadmap 2050) with the "EU Energy Trends to 2030", updated to its latest version in 2009 [EUET2030 2011].

A comparison of the different European energy policies and plans is presented in Table 1:

Table 1: Comparison of European energy policies and plans (Source: FHa based on [ES2020 2010], [ER2050 2011], [EUET2030 2011])

	GHG emissions reduction	Increasing share of RES	Energy efficiency
Energy 2020: A strategy for competitive, sustainable and secure energy (2020)	20% from 1990 values	20%	20% from 1990 levels
Energy Roadmap 2050 (2050)	80% - 95 % from 1990 levels	> 55% *	16% - 20% (2030) 32% - 41% (2050) compared to peak in 2005 – 2006
Energy Trends 2030 - Update 2009 (2030)**	14% by 2020 from 1990 levels	14.8% (2020) 18.4% (2030)	1% from reference scenario (2020, 13 Mtoe) 2% from reference scenario (2030, 27 Mtoe)

*At least 55%, depending on scenarios, range 55% - 97%

** First publication of the Energy Trends 2030 was in 2003, data in the table from 2009, last update.

To achieve these objectives, the EC has established the Directive 2009/28/EC on renewable energy that sets ambitious targets for all member states, i.e. the EU should reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector [2009/28/EC]. The EC also established the Directive 2012/27/EC on energy efficiency [2012/27/EC].

Medium and long term objectives related to energy demand in Europe have been established by the European Commission in the Energy 2020 program: A Strategy for Competitive, Sustainable and Secure Energy (2020) and the Energy Roadmap 2050 (2050). The objectives are ambitious and in order to reduce the use of fossil fuels and to increase security of supply by the promotion of RES mainly. Even though EU country members' objectives are clearly defined by Directives, no policy on concrete measures exists for an advancement of energy storage and its integration into the European energy supply structure. This is in sharp contrast with the necessity presented in this report and the general need to develop energy storage systems contemplated in European energy policy plans.

At member state level only a few countries have introduced specific regulations for electricity storage but specifically for the storage of natural gas (see [FRCES 2013]). The main policy activity today is focused on the realization of a roadmap on energy storage for the EU, “European Energy Storage Technology Development Roadmap towards 2030”, policy recommendations jointly developed by EASE and EERA [EASE 2013]. This roadmap can be seen as a starting point to define significant and relevant energy storage aims in the EU towards 2030.

2.1.3 Quantification of EU energy storage needs

Today, EU’s electricity system storage capacity is around 5% of the total already installed generation capacity. Pumped hydro electricity storage represents the highest share of all large scale electricity storage capacity in Europe (99% worldwide). As postulated widely in [ES2020 2010] and [ER2050 2011], an increase in the global energy and electricity storage capacity will be required in the future. With levels of intermittent RES generation higher than 25% of the overall electricity consumption, the production has to be curtailed in low consumption periods to avoid grid perturbation and grid congestion, unless the RES excess can be stored [FRCES 2013].

New energy storage capacity and technologies will be needed for a future RES based energy supply. Until the development and the implementation of new technologies and capacities PHES as established large scale storage technology and natural gas storage combined with flexible and rapidly responding CCGTs back-up power plants will play an important role in the medium term transition to a RES based energy system in Europe.

Neither the European Commission through the European Energy Programs nor the different energy storage projects realized or being realized in Europe have quantified the energy storage needs in the EU in the medium or long term. Main projects have focused their analyses on the comparison and the potential contributions of individual storage technologies [STORE2.3 2012], [THINKT8 2012]. In [STORE2.3 2012], main scenarios elaborate on future energy structures where electricity fluctuations from a high penetration of RES are assumed to be levelled out by either the existing thermal power plants or by energy storage based on pumped hydro energy storage. An estimation of the deployment of wind energy, being the RES with the highest installed capacity share, as well as an estimate of the PHES capacity required to manage this high penetration are provided.

Main results found with regard to the quantification of future EU energy storage needs are presented in scientific articles by experts in the field of energy storage. Of special interest are the studies of [Heide 2010] and [Heide 2011]. Both studies analyse a highly renewable or fully renewable European electricity system based on wind and solar power and high penetration of energy storage based on hydrogen underground storage in salt caverns.

In [Heide 2011] a scenario based on 100% wind and solar power generation is studied. The required energy storage capacity is estimated to be in the order of 12 – 15% of the annual European electricity consumption which corresponds to 400 –

480 TWh (2007 data), (60% wind and 40% solar power established at the optimal seasonal mixed; wind-only or solar-only would require twice the energy storage capacity). Some of the assumptions and conclusions obtained by the authors are:

- "A storage energy capacity of several hundred TWh represents an incredible large number. For pumped hydro and compressed air storage in Europe this is fully out of reach" [Heide 2011].
- "Excess wind and solar power generation can be used to significantly reduce the required storage needs for a fully renewable European power system" [Heide 2011].
- "The combination of hydro storage lakes and hydrogen storage will be able to contribute solving Europe's search for long term storage" [Heide 2011].
- "Power transmission across Europe is needed to balance local negative power mismatches with positive mismatches in other regions" [Heide 2011].

Final results presented in [Heide 2011] for an estimated EU fully renewable energy power system (assumptions: 1,300 GW wind power, 830 GW solar power, 50% excess generation) requires a hydrogen storage system of 50 TWh and 220 GW for energy capacity and discharge power respectively (assumptions: 60% electrolyser efficiency, 60% fuel cell efficiency, hydrogen underground storage). Taking into account that a typical large cavern field has a volume of $8x10^6$ m^3 [LRI 2010], it would provide an energy storage capacity of 1.3 TWh [Heide 2011]. The required amount of energy storage could be covered by 39 large salt cavern fields with hydrogen storage.

Beyond the electric sector, less attention is being paid to the storage of natural gas and even less to the one of petroleum and its products. Natural gas storage is being used in Europe at seasonal scale, to balance the different gas network consumptions from summer (low) to winter (high because of the heating systems) and to assure supply during short periods of time in case of geopolitical instabilities (for natural gas working volume and storage capacity see annex 5.4). Other solutions like Power-to-Gas and methanation are receiving increased interest with regard to the facilitation of RES integration.

The conclusion of this section is that, although a thorough quantification of the energy storage needs in the EU has not been undertaken yet, the necessity of energy storage to compensate the intermittency of RES is obvious and that energy storage will play a key role in the future European energy structure, as it is described in the Energy 2020 program and the Energy Roadmap 2050 by the EU. The quantification of the energy storage capacity required in the medium and long term and the establishment of European and individual member state objectives will allow greater penetration of RES in the EU energy mix in a planned approach towards 2050. A coming roadmap on energy storage for the EU or adequate documents will have to define these goals and will have to establish a well-defined program.

Regarding results presented in [Heide 2011], hydrogen underground storage is presented as a really promising technology due to its high volumetric energy storage density and the fact that hydrogen storage in caverns is already standard practice. Even the most ambitious case of RES integration (100%) seems to be feasible by the implementation of a huge but not unrealistic amount of hydrogen energy storage. Taking into account that the penetration of RES in the energy mix by 2050 would be less than estimated, and taking also into account that other technologies like PHES will contribute to the energy management, and other solutions such as high voltage transmission lines are defined as a priority, with a plan to develop energy storage capacity in medium and long term, the objectives established in the Energy Roadmap 2050 could be fulfilled without major problems.

2.2 *Options for renewable electricity integration*

It is a prerequisite for the stability and security of electricity supply to balance the (varying) power generation with the (varying) electricity demand at any time and at any point of the electricity network. The intermittent nature of the main share of renewable energy sources (wind, PV) is the main challenge for today's power systems.

Energy storage is not a stand-alone technology to facilitate the integration of the renewable electricity supply to the energy supply system.

Main complementary technology options to energy storage for integrating variable renewables are shown in Figure 1:

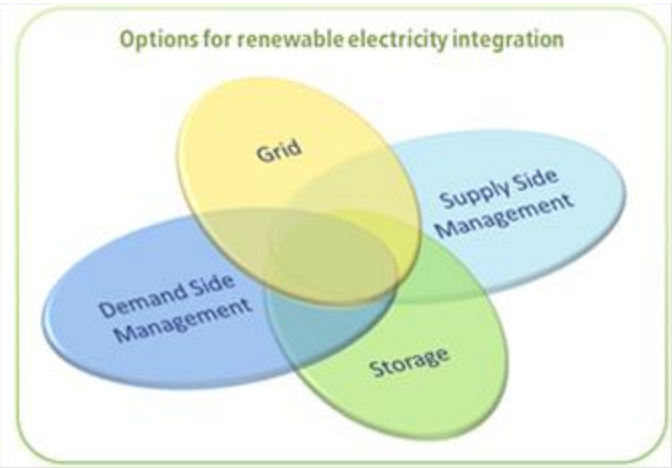


Figure 1: Options for renewable electricity integration

- electrical grid modernization and improved operation schemes at all voltage levels (transmission and distribution grid expansion and upgrade, including interconnections of different smart grid elements; improved planning, operation and grid management),

- supply side management (improved flexibility of conventional generation, centralized and decentralized),
- demand side management (e.g. metal industry, chemical industry, paper industry, households, e-mobility, etc.).

None of these options provides a universal solution. On a long term only the coordinated interaction between options such as generation, transmission, distribution, storage and consumption of electrical energy facilitates effective integration of renewable energy generated in the power supply system. These options are to some extent interchangeable.

2.2.1 Grid Management

Increasing shares of renewable electricity such as fluctuating wind power and photovoltaics, rising cross-border flows due to commercial transactions as well as security and reliability of supply require extensions of the electrical grid.

Various studies have analysed the deployment of renewable energy and the need for infrastructure expansion in the European power supply and on regional level ([SUSPLAN 2011], [dena 2010], [TYNDP 2012]).

The results show that significant non-transmittable power across borders between neighbouring countries is available in Europe as well as inside the countries and on regional revel.

As a result, a necessary grid extension of approximately 52,300 km of new or refurbished extra high voltage power lines across Europe was identified, requiring a total investment of € 104 billion [TYNDP 2012, pp. 14, 17].

High grid expansion and modernization needs were identified both in the transmission and in the distribution grid. The need for distribution grid expansion should be analysed in detail at national level, e.g., a German study identified a necessary distribution grid extension of new lines:

- low voltage: 51,563 km or 4.4% (existing 1,160,000 km)
- medium voltage: 72,051 km or 14.2% (existing 507,210 km)
- high voltage: 11,094 km or 14.5% (existing 76,279 km)

Additionally, 24,500 km of modification needs in the high voltage grid have been identified. In total, the required investment amounts to € 27.5 billion (scenario NEP B 2012, until 2030 [dena 2012, p. 8]).

Different possible future scenarios for renewable electricity in Europe result in different requirements for the extension and investment needs of the electricity networks. Notably, the transmission grid expansion is a very long process (5-10 years, in specific cases up to 20 years) that requires major investments as well as a long term permission process at European level. Land use and other environmental impacts are playing an important role. In the past, many interconnector and transmission grid projects were not implemented in time or not realized at all [BNetzA 2011], [BNetzA 2012], [TYNDP 2012]. This may lead to increased storage needs in the next few years.

However, unlimited transmission capacity alone will not be sufficient to ensure security of supply in an energy systems completely based on renewables.

2.2.2 Supply Side Management

Supply Side Management (SSM) means the improvement of flexibility of the conventional generation mix or dispatchable renewable power plants (e.g. biofuel, biomass, solar / wind power with energy storage). The flexible power plants contribute to the stabilization of the electricity grid.

Future conventional power plants have to meet the following requirements to compensate the fluctuating input of renewable electricity and to stabilize the electricity grid:

- frequent start-up and shutdown,
- quick response capability,
- higher ramp rates,
- extension of load range (decreasing ”must run”),
- improved operation efficiency during part load.

Power plants have different characteristics making some more suited to supplying certain needed functions. Coal-fired power plants are not sufficiently flexible; nuclear power plants are inflexible to a large extent (base load). [arrhenius 2011] concludes that from conventional power plants only gas-fired power plants can meet all requirements resulting from an increased electricity production from fluctuating renewable resources.

More flexible conventional power plants can reduce the need for DSM, energy storage and/or grid upgrading and grid expansion.

In order to increase their flexibility, the existing conventional power plants need to be modified. The additional costs of a retrofit have to be compared with the costs of a new (flexible) plant and the costs of different other options (e.g. energy storage) in order to get the optimum economic solution.

In case of an electricity system entirely based on renewables, adapted gas engines and gas turbines can be applied operating on biomethane, e-methane or hydrogen.

2.2.3 Demand Side Management (including e-mobility)

Demand Side Management (DSM) comprises the mechanisms to actively manage customer energy consumption in response to supply conditions. DSM is achieved by shifting energy consumption from hours of high electricity demand (peak) to hours of low electricity demand (off-peak). Multiple units connected to the power supply can participate in a DSM system.

Large industry and large commerce

Large scale electricity consumers in industry and commerce are, e.g., paper and chemical industry, glass industry, cement industry, steel industry, food industry, etc. Facilities the shutdown of which does not cause impairment of the production process (e.g. refrigerators, freezers, air compression, processes of paper production, stone mills in mines, ventilation and air conditioning) are generally suitable for DSM.

E.g., [FfE 2010] has examined theoretical and technical DSM potentials of different industries in Germany. Figure 2 shows that the technical potential is significantly decreasing by increasing shutdown periods, e.g., the technical DSM potential for 4 h shutdowns accumulates only to an amount of 1 GW. From the authors' point of view the relative results can be generalized at European level for the industry sectors investigated.

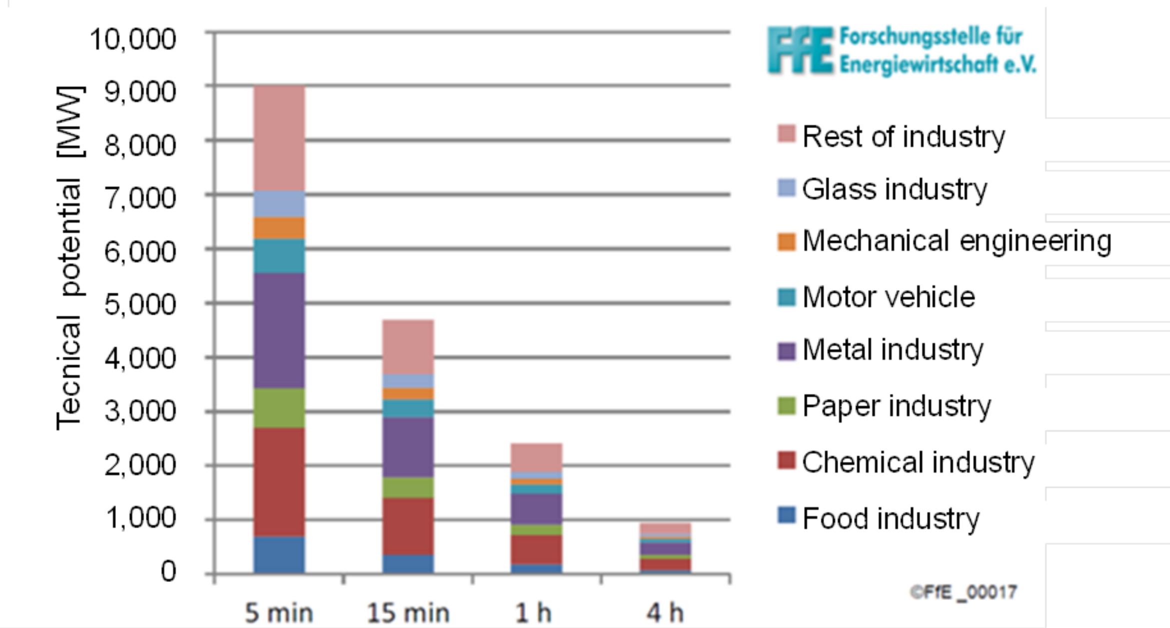


Figure 2: Technical potential of interruptible power for various industry segments related to the shutdown time [FfE 2010, p. 15]

The economic / practical potential is often much lower than the technical potential due to potential effects on the production process caused by the shutdowns.

For all load displacement processes it is important to note that after a load reduction phase, a phase with secured power supply has to follow. DSM as an option for renewable energy integration does not reduce total energy demand as it only allows for a timely shift of consumption, but could be expected to reduce to some extent grid expansion needs, conventional generation reserve needs and/or energy storage needs.

In case of large industry and large commerce DSM can shift energy consumption on an hourly basis, i.e. for minutes and a few hours, but not for days or weeks.

Under no circumstances this option alone will be sufficient to shift large amounts of energy over longer periods which will be needed in an energy system completely relying on renewable energy.

Small commerce, services and households

Small DSM is widely discussed as a promising option to allow a high penetration of renewable electricity. Household refrigerators, washers, dishwashers and dryers are some typical small appliances with potential DSM connectivity.

Figure 3: Options for small DSM applications [VDE 2012, p. 122]

The theoretic potential of DSM in households is very high. A German study calculated the theoretic potential to be 18 GW for German households in 2020 and 35 GW in 2030. In contrast, the technical / practical potential is 3.8 GW (12.4 TWh/a) by 2020 and 6 GW (32.3 TWh/a) by 2030 [VDE 2012, p. 126). The technical / practical potential is very limited due to several factors: consumer comfort level, need of smart meter installation, necessary IT networks, additional infrastructure costs, safety issues, etc. The potential growth in the future is mainly due to the possible expansion of e-mobility, heat pumps, CHP and air conditioning systems.

The estimations of the technical / practical DSM potentials bear a high degree of uncertainty as they are based on unknown future framework conditions. Also the forecasted technical potentials for load shifting in households may significantly decrease because of the highly increasing energy efficiency of modern home appliances. According to [EREN 2012, p. 74] “the combined DSM potential of all ‘smart’ household appliances in Germany in 2020 is equivalent to around 0.1% of peak demand”. Currently, practical experience with DSM exists notably in large industry and large commerce [VDE 2012].

e-mobility

The integration of e-mobility into DSM through controlled charging / discharging of battery electric vehicles has been pinpointed to develop as a potential option in the future. Currently, the electric mobility market in Western Europe is at an introductory stage, but it is expected that large numbers of EVs will be deployed by 2030-2050. Table 2 gives an overview of e-mobility targets in various countries.

Table 2: Selection of e-mobility targets [ICCT 2012], [GTAI 2011], [Chardon 2010]

Country	Targets / Scenarios*
Germany	1 million cumulative EVs (BEVs, PHEVs, FCEVs) by 2020, 5 million by 2030
UK	1.2 million cumulative EVs by 2020, 3 million by 2030
France	2 million cumulative EVs/PHEVs by 2020
Spain	500,000 EVs by 2015
Netherlands	1 million cumulative EVs
China	500,000 cumulative EVs by 2015 and 5 million by 2020

*EV = Electric vehicle, PHEV = Plug-in hybrid electric vehicle, FCEV = Fuel cell electric vehicle, BEV = Battery electric vehicle

The potential utilisation of battery electric vehicles for load shifting (dispatched battery charging) has been widely discussed. A part of it is the vehicle-to-grid concept (V2G): the EV can feed back to the grid by battery discharging.

The following requirements are essential for the successful participation of the EVs in a DSM system:

- a certain number of EVs with sufficient storage capacity have to be available,
- each EV has to be equipped with a control unit enabling dispatch,
- each EV has to be connected to the charging / discharging unit in the required time frame,
- extra communication hardware is required for V2G participation,
- acceptance of the EV owner to participate in the DSM system is required.

An IEA study [IEA 2010] has investigated the potential benefits of using EVs in load shifting and V2G applications for Western Europe and worldwide up to 2050. The report confirmed that load shifting for smoothing short term fluctuations with V2G is beneficial and can reduce the required energy storage capacity. "Simulations previously undertaken suggested that without load shifting, a worldwide energy storage capacity ranging from 189 GW to 305 GW would be necessary. With load shifting, the range of required energy storage capacity was reduced to 122 GW to 260 GW" [IEA 2010, p. 55].

The integration of e-mobility into DSM systems can shift energy consumption at an hourly basis, not for days or weeks, e.g. the DSM potential of all expected EVs in Germany in 2020 is about 2 GW for negative reserve power during 8 hours[1].

Not only the limited battery capacity, but also the daily use of the EVs is a challenge for the EV usage to become part of a DSM system. Unregulated charging of EVs can even contribute to an increase of peak load and lead to grid overloads [Salah 2012].

[1] Assumptions: average battery charging power 2 kW/EV, average battery capacity 16 kWh/EV

The “rush hour of electricity” follows the rush hour in traffic. A suitable charging system communicating with the power networks as well as suitable electricity tariff structures could be a solution for this issue. Specific tariffs providing incentives for the vehicle users encouraging them to charge in times with high wind and low loads are required.

Also, plug-in hybrid electric vehicles and hybrid concepts with direct battery charging capability are another important option in the context of integrating fluctuating renewables into the electricity system. The use of PHEVs in DSM systems could have similar implications as the one of BEVs.

“In the case of hydrogen fuel cell electric vehicles, hydrogen production via water electrolysis can [also] include demand response options. The number of ‘smart grid’ elements involved in demand response is significantly lower, installed power capacities are significantly higher and transaction costs are thus lower compared to BEVs” [EREN 2012, p. 76].

Figure 4: Example for capabilities of PEM electrolysers for hydrogen production in DSM systems [Waidhas 2011]

Hydrogen is a multi-purpose fuel that can be used at large scale during and after the restructuring of the energy system towards a 100% renewable energy system.

DSM conclusions

In summary, it can be stated that:

- Theoretical load shift potentials exist already today in industrial areas as well as in households and in the small commerce sector. In particular peak loads lasting minutes can be reduced by the application of DSM.
- Currently, the practical applications of DSM are limited to industry as there significant energy cost reductions can be realized. Other DSM strategies / applications in the residential, small-commercial and mobility sectors do practically not exist as of today but can be momentous for the future.

- All DSM participants, large or small, require additional “smart grid” elements. Acceptance is required from both the utilities and the customers in order to enable the connection to and the interaction with the electricity grid.
- In most cases the implementation and/or the increased utilisation of practical DSM potentials require new investments. These investments have to be compared with alternative solutions such as investments in storage systems or grid extension.
- The potential of DSM for electricity load management will also in the future remain limited to an hourly level.

2.2.4 Energy Storage

Even if all afore-mentioned non-storage options for renewable energy integration are perfectly realized, there still remains a need for energy storage:

- for valorisation of excess renewable electricity,
- to match energy supply with demand,
- to provide assured power capacity at “low-wind & low-sun” times,
- for the transition to flexible conventional power plant operation characteristics,
- to increase grid stability, system black-start capability and local supply security.

Subject to regional conditions, energy storage may be more important than grid extension.

Different energy storage technologies are available and have been assessed thoroughly. The next section gives an overview of relevant large scale energy storage technologies, such as pumped hydro energy storage, compressed air energy storage, stationary batteries and Power-to-Gas systems. Storage options for small scale applications are not included.

2.3 *Relevant large scale energy storage and assessment of storage technologies*

2.3.1 Pumped Hydro Energy Storage

2.3.1.1 Principle, technical characteristics

In PHES plants, electrical energy is stored in the form of potential energy of water. When demand is low the plant uses electrical energy to pump water from the lower reservoir to the upper reservoir. In times when demand is high and electricity is more expensive, this stored potential energy is converted back into electrical energy: water from the upper reservoir is released back into the lower reservoir. The turbines generate electricity. Figure 5 shows a principle schematic of a PHES plant.

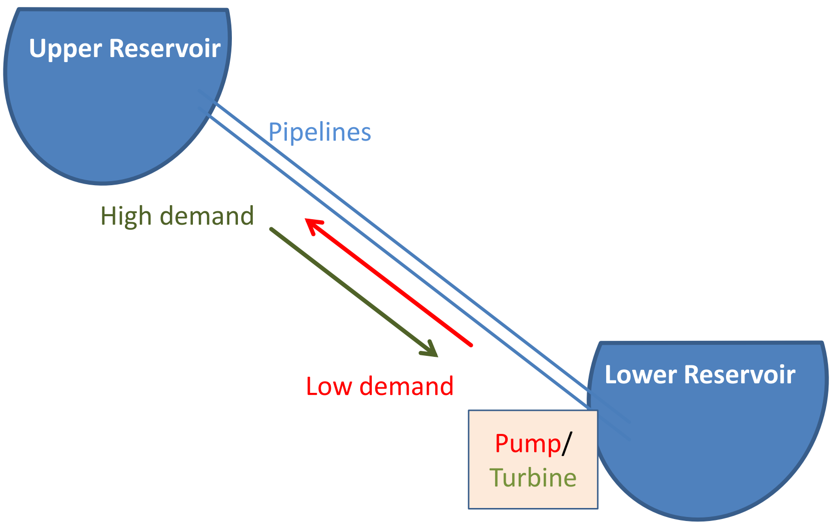


Figure 5 **A principle schematic of a PHES plant (Source: LBST)**

The installed power of PHES is in the range of 10 MW to about 1 GW. Typically, the storage capacity is from 6 up to 10 full load hours of the power plant[2]. This type of storage plant can quickly respond to energy demands (60 – 120 s). PHES energy efficiency varies in practice between 70% and 85%. In general, PHES plants have very long lifetimes (50 years and more) and practically unlimited cycle stability (over 15,000 cycles).

2.3.1.2 System integration

PHES is currently the electricity storage technology providing the largest storage capacities. The main applications are energy management through time shift as well as provision of power quality and emergency supply.

[2] An exception is the Austrian PHES Limberg with over 60 hours of charging / discharging time [Limberg AT 2013].

PHES systems can be classified between storage systems for medium term (minutes to hours) and long term storage (days and beyond).

Currently a trend can be noticed, that existing plants are operated more and more (shorter) cycles per day. However, the storage capacity remains limited by the reservoir capacity.

2.3.1.3 Existing implementations

Currently PHES is the most widely used form of bulk electricity storage. PHES accounts for more than 99% of bulk storage capacity worldwide: around 127,000 MW [EPRI 2011].

"The energy storage in the EU energy system (around 5% of total installed capacity) is almost exclusively from PHES, mainly in mountainous areas (Alps, Pyrenees, Scottish Highlands, Ardennes, and Carpathians)." [EU 2013, p. 1]

Currently, the total installed capacity of PHES in EU-27 (+ Norway, Switzerland and Turkey) amounts to about 51 GW; 6 GW are under construction (complete list of PHES plants in annex 5.5).

2.3.1.4 Potentials for large scale energy storage

The main disadvantage of PHES is the limited potential for expanding the number of PHES due to its dependence on topographical conditions and potential environmental impacts.

Compared to the expansion of renewables, the existing PHES capacity in central Europe is quite limited. Figure 6 compares the potential development of renewable electricity in EU-27 to the expansion targets of PHES until 2020.

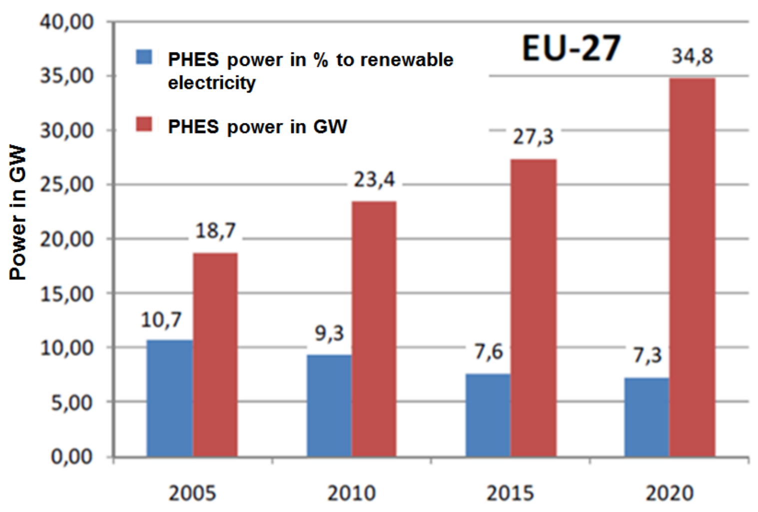


Figure 6: Development of absolute und relative power of PHES in relation to renewable installations in EU-27 [VDE 2012a, p. 125]

The installed power of PHES in EU-27 will about double by 2020 as compared to 2005 amounting to 34.8 GW then. But in the same time frame, the ratio between installed renewables to installed PHES power will decrease from 10.7% to 7.3%. In other words, the expansion of PHES power cannot keep pace with the rapid expansion of renewables [VDE 2012a].

Another option is to develop the existing Norwegian hydropower capacity to become Europe's green battery (maximum storage potential of 84 TWh) [Heinemann 2011, p. 9]. More transmission lines to connect Norway with central Europe, new infrastructure and market improvements are essential to realize this idea.

Potential future developments:

- modification (retrofit) of existing PHES: power increase of pumps and turbines; variable, ultra-fast reacting generation,
- underground PHES in closed mines: several new underground PHES projects have been proposed and are currently in the research phase (e.g. [EFZN 2011]),
- gravity power technology: in-ground, closed loop modular pumped storage hydro power applying a large piston (e.g. cut from rock or manufactured from cuttings and concrete) lifted and lowered to store respectively produce electricity (e.g. [Gravitypower 2013]),
- in the sea: very large and hollow spheres located at sea ground using the enormous water pressure; when cheap electricity is available water is pumped out of the spheres; when electricity is needed water is let back into the spheres while powering turbines (e.g. [Zanter 2011]).

2.3.2 Compressed Air Energy Storage

2.3.2.1 Principle, technical characteristics

In CAES plants, electrical energy is stored in the form of potential energy of air. When electricity supply is higher than demand, electricity is used to compress air and store it underground (caverns, aquifers, mines) or above-ground in vessels or pipes. When demand exceeds supply, the compressed air is mixed with natural gas, burned and expanded in a gas turbine. Figure 7 shows a principle schematic of a CAES plant.

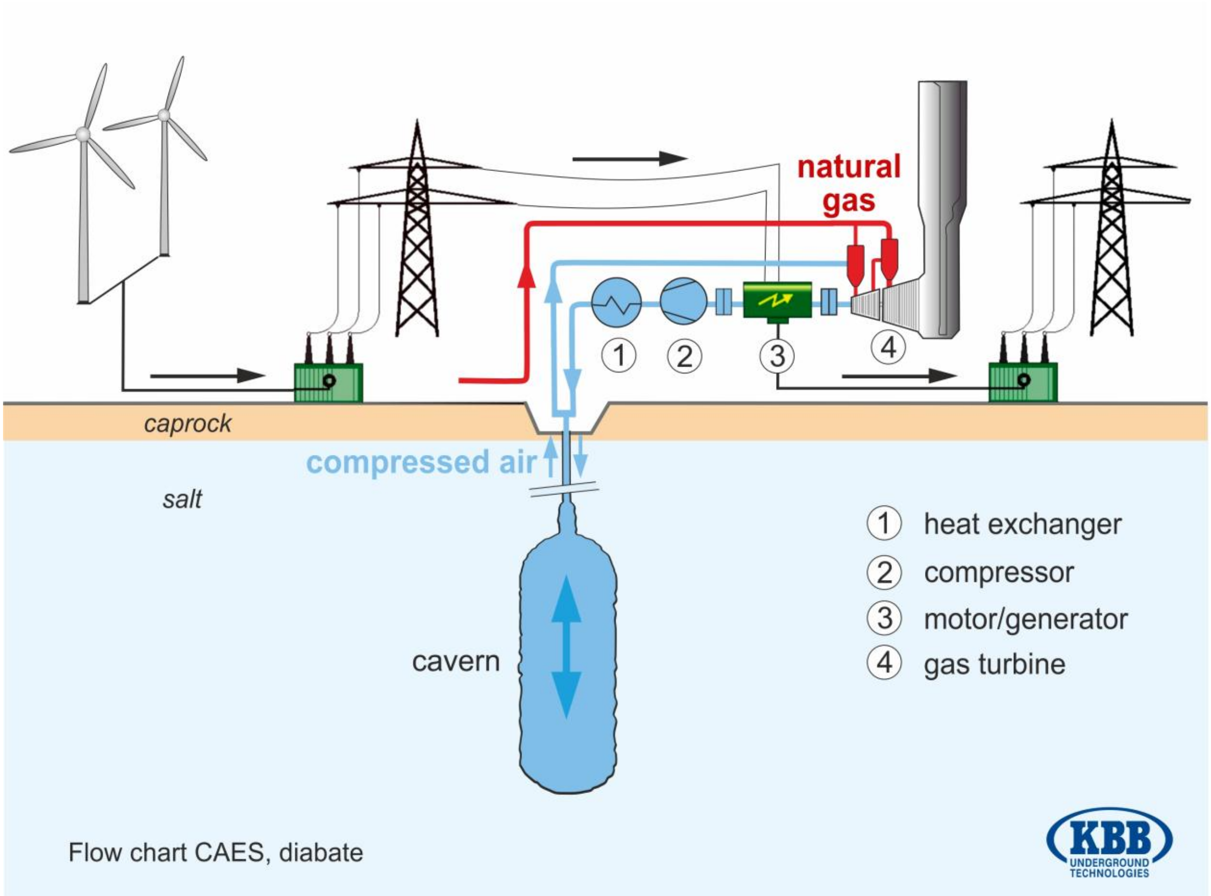


Figure 7: CAES plant with underground storage (Source: KBB Underground Technologies GmbH)

The installed power of CAES plants is in the range of 10 MW up to 1 GW. The storage capacity of CAES plants is determined by the volume of the existing storage (e.g. salt cavern) and the air pressure. The response time of CAES is in the minute range. CAES plants have a lifetime of 25+ years and a cycle lifetime of >10,000 cycles.

In conventional CAES plants the heat released during compression needs to be dissipated by cooling and is not stored, this is the reason why later the air must be reheated prior to expansion in the turbine. Without heat recovery, the round-trip efficiency of diabatic CAES is in the range of 42% (see Table 4), with heat recovery some 54%.

2.3.2.2 System integration

The principal applications of CAES plants do largely correspond with that of PHES.

CAES plants can be classified as storage systems for short to medium term (minutes to hours to a day) storage times.

2.3.2.3 Existing implementations

Currently, only two diabatic CAES power plants are in operation worldwide. Table 3 summarizes the main characteristics of these plants.

Table 3: Examples for CAES power plants [VDE 2009]

Country	Huntorf, Germany	McIntosh, Alabama, USA
Year	1978	1991
Storage: salt cavern	2*150,000 m^3	1*538,000 m^3
Power	321 MW for 2 hours	110 MW for 26 hours
Operating pressure	5.0-7.0 MPa	4.5-7.6 MPa
Efficiency	42%	54%

2.3.2.4 Potentials for large scale energy storage

CAES represents a storage technology especially at larger scale (by storage in mines or salt caverns). It shows a lower geographic limitation of locations compared to PHES plants. The disadvantage of CAES is its low round-trip efficiency.

Potential future developments:

- Adiabatic compressed air energy storage (ACAES): With heat storage in an ACAES plant it is possible to realize efficiencies of up to 70%. The heat of compression developing during charging is stored and later used for heating up the compressed air before its expansion in the turbine. The German utility RWE is planning to erect a demo ACAES (90 MW, 360 MWh) named "ADELE". Provided economic feasibility is given, start of demo operation is planned after 2019 [RWE 2012, RWE 2013, RWE 2013a].
- Low-temperature compressed air energy storage (LTA-CAES): In order to avoid high temperatures in parallel to high pressures, experts at Fraunhofer UMSICHT have developed an LTA-CAES plant based on two-tank non-thermocline thermal energy storage (TES). They "selected and designed multistage radial compressors and expanders with single stages arranged at the ends of several pinion shafts rotating with different - and for the assembled impellers optimal - speeds. The proposed LTA-CAES design shows cycle efficiencies in the range of 58 to 67%, slightly lower compared to those envisioned for high temperature ACAES" [Wolf 2011].
- Isothermal compressed air energy storage (ICAES™) – notably for small applications [SustainX 2013], [LightSail 2013]. SustainX has built a pilot plant at its headquarters in Seabrook, New Hampshire, USA, with field demonstrations planned for 2014. Regenerative air energy storage: first product of LightSail, California, USA: LightSail RAES-V1 (power 250 kW, capacity 1 MWh, efficiency 70%) [LightSail 2013].

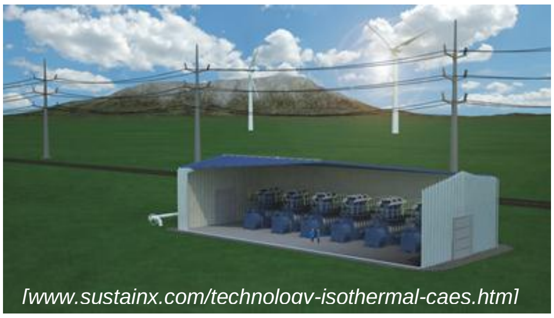


Figure 8: Isothermal compressed air energy storage (Source: www.sustainx.com/technology-isothermal-caes.htm)

2.3.3 Stationary batteries

2.3.3.1 Principle, technical characteristics

An electrical battery is a combination of several electrochemical cells, used to convert stored chemical energy into electrical energy. Various battery technologies and chemistries are known today: lead acid (LA), lithium ion (Li-ion), sodium sulphur (NaS), flow batteries, etc. Stationary batteries are rechargeable. In order to provide larger storage capacities, batteries can be combined to battery banks.

Batteries can deliver power in the kW - MW range while storage capacity is in the kWh - MWh range (battery banks). Batteries are capable to respond very fast to changes in energy demand (within milliseconds). Typical discharge times are up to several hours.

In general, lifetimes of batteries are relatively short (5 – 15 years) and also the number of charge / discharge cycles is limited (LA: ~500 cycles; NaS: ~10,000 cycles depending on depth of discharge and further operating parameters).

2.3.3.2 System integration

Batteries can be installed close to wind farms or PV plants or be coupled to the electricity grid. Technology, optimum size and location have to be determined case by case. No single cell type is suitable for all applications.

Several types of batteries can provide energy storage and other important ancillary services. Batteries can be classified as systems for short term electricity storage (up to several hours).

It is to mention that in case of flow batteries capacity and power rating can be scaled separately as electrolyte tanks and fuel cells are separate components. In these systems, the electrical storage capacity is limited only by the capacity of the electrolyte tanks. Flow batteries are suitable for energy storage during hours to days with a power of up to several MW.

2.3.3.3 Existing implementations

Today, batteries are mainly used in consumer electronics and cars.

Batteries in the range of several MW (10 MWh) are state of the art. But in [EU 2013], it is mentioned that “there is no battery technology capable of meeting the demanding performance requirements of the grid: high power, long service life time, low cost.”

Batteries today account for less than 1% of the worldwide installed storage capacity for electrical energy, mainly for excessive cost reasons:

- Lead Acid: ~35 MW (~70 MWh),
- Lithium Ion: ~70 MW (~17 MWh),
- Sodium Sulphur: ~316 MW (~1,900 MWh),
- Nickel Cadmium: ~27 MW (~6.75 MWh),
- Redox Flow: ~3 MW (~12 MWh).

[EPRI 2011], [EU 2013], [IEC 2011] (status 2010)

2.3.3.4 Potentials for large scale energy storage

Large battery systems are believed to represent an important part of the electricity delivery system especially for electricity storage in the future for short to medium term storage (minutes, hours to days) and capacities in the MWh range. Yet, it has also been predicted that they will not become suitable for long term storage (days to months) and large capacities (GWh to TWh).

2.3.4 Power-to-Gas

2.3.4.1 Principle, technical characteristics

The so called Power-to-Gas route includes Power-to-Hydrogen and Power-to-Synthetic Methane. In some literature also Power-to-Liquid, power-to-Chemicals, Power-to-Materials, etc. are summarized as Power-to-Gas technologies. The common component for all paths is the first step of hydrogen production. Figure 9 shows schematically the basic concept of the Power-to-Gas technology. Excess renewable electricity can be used to produce hydrogen from water. The generated hydrogen can be stored in various ways: underground salt caverns, underground tubes, pressure vessel bundles or bound in other chemicals.

Hydrogen can be used for re-electrification for power balancing (GT, CCGT, FC), as raw material directly in industry (oil refining, steel, glass, hydro treating, etc.), as fuel in the transport sector and for heating purposes.

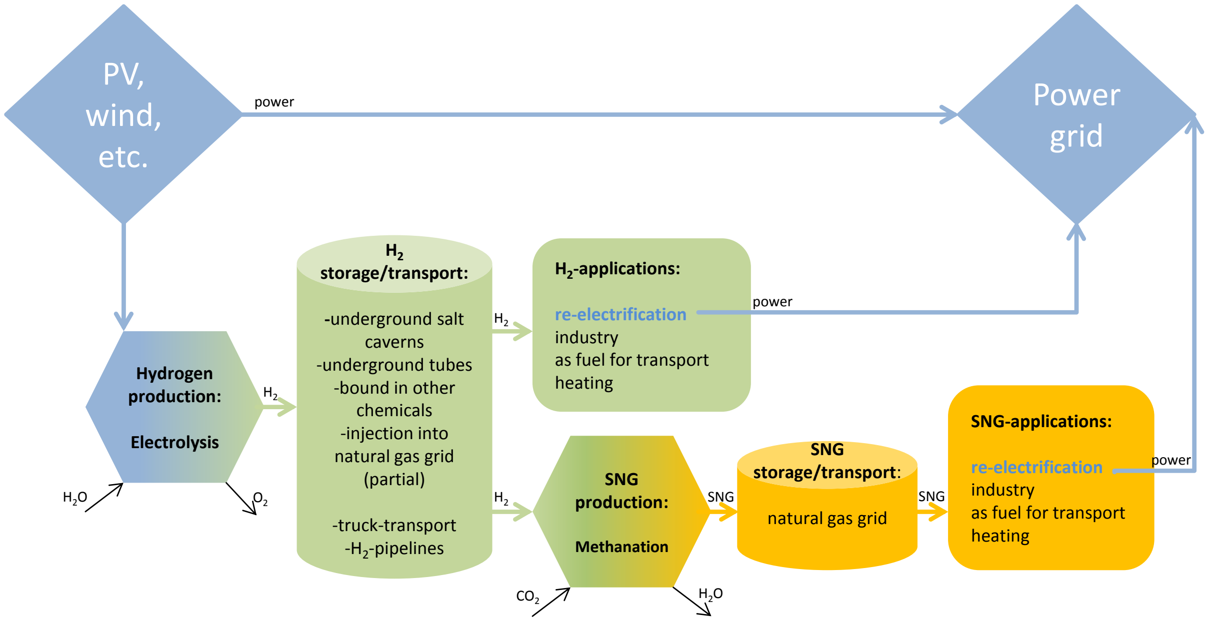


Figure 9: Basic concept of Power-to-Gas (Source: LBST)

Furthermore, hydrogen can be used for the production of synthetic liquid fuels (petrol, diesel, kerosene and methanol) compatible to existing infrastructure and engines [SunFire 2013].

Instead of storing it directly, hydrogen could also be injected into the natural gas grid to a certain extent and thereby using the existing storage and distribution capacity in the grid. The injection of hydrogen into the existing natural gas infrastructure has been investigated in several projects such as NaturalHy [NatHy 2006]. Furthermore, GERG, the European Gas Research Group, has initiated a project entitled "Admissible hydrogen concentrations in natural gas systems" in order to answer the question of hydrogen injection into the natural gas grid on a European level and aims for the establishment of a common European standard [GERG 2013]. Currently, the results of the studies do not provide a final answer on the possibilities to add hydrogen into the natural gas grid. Especially for storage sites further investigations are required.

Another possibility for large scale hydrogen storage is a process to generate synthetic natural gas (SNG) from hydrogen and carbon dioxide (CO_2). The resulting SNG can be fed into the existing natural gas grid without any limitations. The grid including its storage capacities can be utilised for storing and distributing the SNG. As SNG fulfils all requirements of conventional natural gas, it can be directly used for any natural gas applications such as gas turbines, combined cycle power plants, heating appliances, CNG vehicles, etc. and even more make unlimited use of the existing pipeline and storage infrastructure.

The installed power of Power-to-Gas systems is expected to be in the range of 10 kW to several GWs. The storage capacity is in the range of hours to several weeks. The system efficiency is depending on the efficiency of all system components: hydrogen production, storage, transport, (methanation), etc. Full cycle efficiencies from 20% to 40% can be achieved depending on the chosen components and pathway. Efficiencies of SNG chains are about 10% lower than that of direct hydrogen Power-to-Gas chains. On the other hand, the energy density of natural gas storage is a factor of 5 higher (when comparing systems with a pressure difference of 13 MPa).

2.3.4.2 System integration

The Power-to-Gas technology provides the potential for bulk power and long term energy storage (days, weeks, months).

Beside applications in the transport sector, hydrogen or SNG can be used for stationary applications, e.g., in peak power plants deploying gas turbines in the several hundred MW range.

Hydrogen storage in, e.g., underground salt caverns is useful to provide grid energy storage for intermittent energy sources as well as providing fuel for the transport sector, raw material for industry or for heating purposes. SNG storage in the whole natural gas grid is another relevant option, specifically in short term, but with high energy losses and challenges concerning the availability of ample cheap and easy accessible CO_2 sources in the long term.

2.3.4.3 Existing implementations

In general, all components for the implementation of Power-to-Gas storage systems are more or less commercially available, but require further research and development before they can be applied in commercial large scale energy storage systems. Large scale units have not been realized yet.

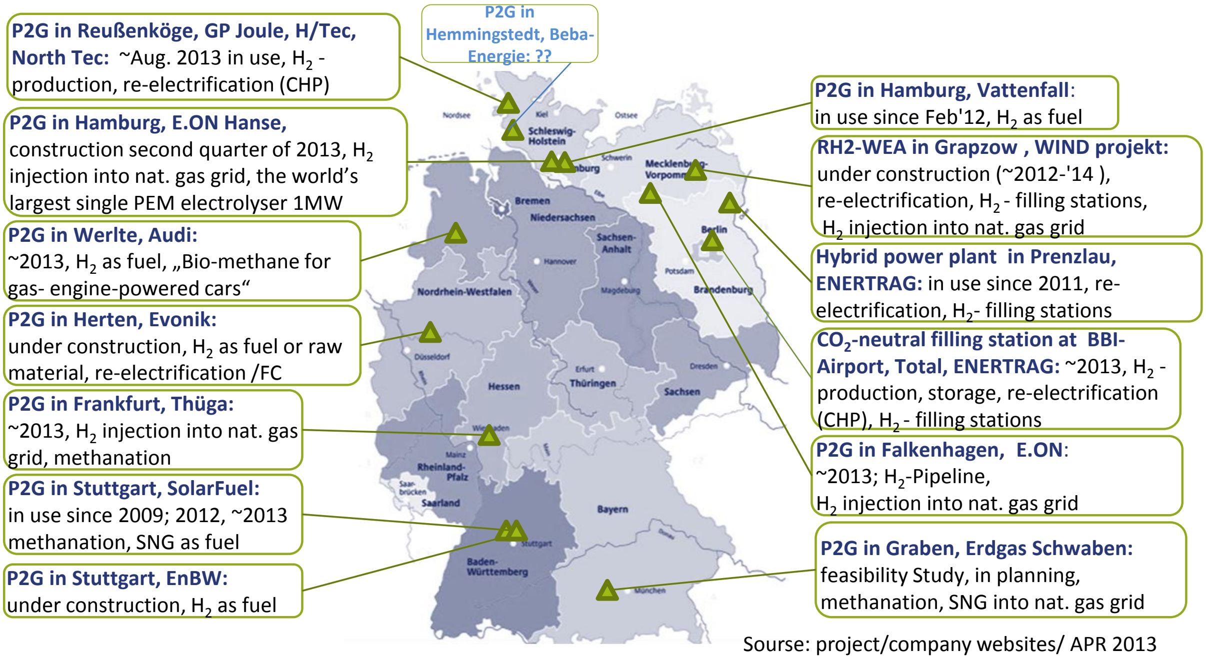


Figure 10 provides an overview of demo projects in Germany for producing hydrogen and methane from renewable power.

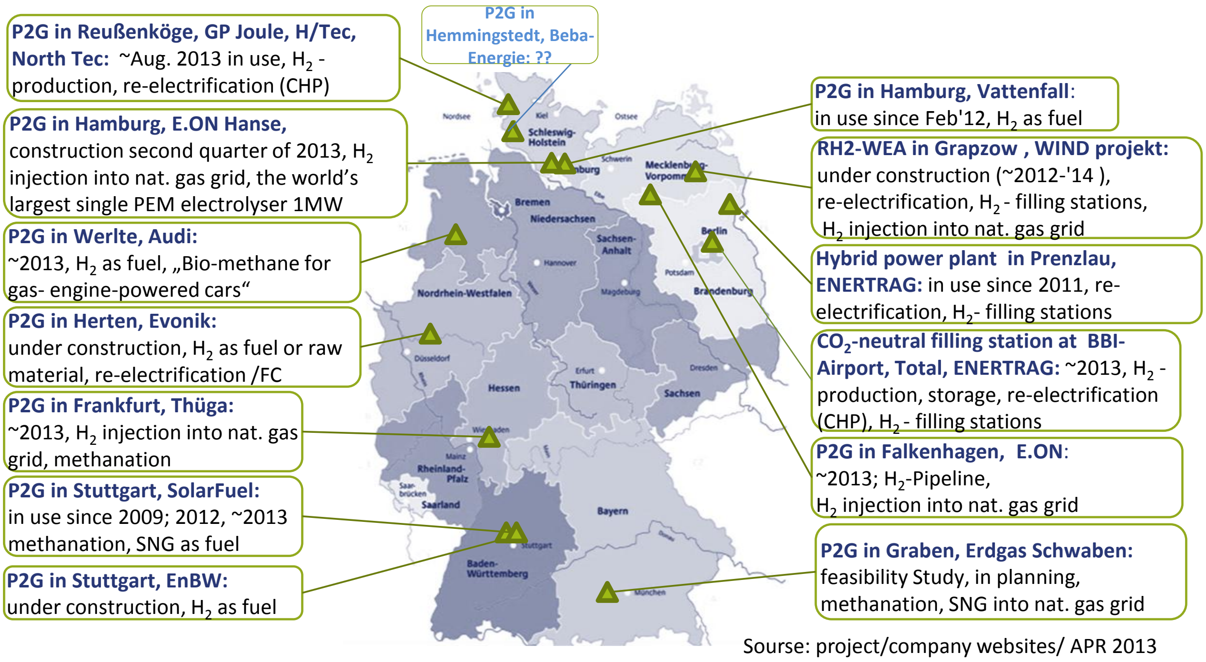


Figure 10: Power-to-Gas – demo projects in Germany 2013 (Source: LBST based on project / company websites)

Storage, distribution and power conversion technologies for natural gas are state-of-the-art and commercial unlike hydrogen technologies [Sterner 2009, p. 107]. The Power-to-Gas technology, notably hydrogen applications require further research and demonstration activities.

2.3.4.4 Potentials for large scale energy storage

Power-to-Gas technologies (H_2 or SNG) are very important options for large scale energy storage (capacities in the MWh - TWh range) and for short to long storage periods (hours, days, weeks, months).

Storage, distribution and power conversion technologies for natural gas are state-of-the-art and commercial unlike hydrogen technologies, as already mentioned in the chapter “Existing implementations” [Sterner 2009, p. 107]. In the long run, renewable gas from Power-to-Gas technologies can gradually replace conventional fossil natural gas using the same infrastructure.

Some challenges may be caused both by the lack of an area-wide hydrogen infrastructure and the required modifications / adaptations of the existing gas-fired power plants. In order to overcome these challenges and to assess the potentials, which the existing natural gas grid including its various storage capacities (salt caverns, aquifers, depleted natural gas fields) offers, further research and development activities are urgently needed. The main challenge for Power-to-Gas without methanation remains with the limitation of hydrogen admixture into the natural gas grid.

2.4 ***Benchmarking of large scale storage technologies***

2.4.1 Assessment of technical storage performance

Energy storage is an essential technology to facilitate the integration of renewable electricity into the energy system.

Starting from their technical parameters the various storage technologies are offering different characteristic properties which are of high relevance for technology selection.

Table 4 provides a comparison of different large scale energy storage technologies including stationary batteries. All battery technologies are showing a relatively low storage capacity (energy rating). Therefore, the main application for battery technologies is in mobile and isolated network applications. Because of the existence of more appropriate solutions, their application for long term storage on a European scale is not expected. The comparison of literature concerning Power-to-Gas systems shows a wide range: power rating is in the range of 1 kW to several GWs, the storage capacity is in the range of hours to several weeks (see Table 4).
To provide a meaningful comparison, the four following relevant Power-to-Gas system scenarios have been compared and therefore for these precise data are given:

- hydrogen production 233 $MW_{el.in}$ electrolysis, hydrogen underground storage in salt caverns for later H_2 re-electrification in a 650 $MW_{el.out}$ combined-cycle gas turbine (efficiency 60%);
- hydrogen production 343 $MW_{el.in}$ electrolysis, production of synthetic natural gas from hydrogen and carbon dioxide via methanation, SNG underground storage in salt caverns, later SNG re-electrification in a 650 $MW_{el.out}$ combined-cycle gas turbine (efficiency 60%);
- hydrogen production 8 $MW_{el.in}$ electrolysis, hydrogen underground tube storage (charging time 1.5 days) for later H_2 re-electrification in a 18.1 $MW_{el.out}$ fuel cell;
- hydrogen production 8 $MW_{el.in}$ electrolysis, hydrogen storage in pressure vessel bundles (charging time 1.5 days) for later H_2 re-electrification in a 0.7 $MW_{el.out}$ fuel cell.

It clearly shows that from the scenarios investigated the only feasible option for large scale energy storage is to employ underground hydrogen / SNG storage in salt caverns. SNG provides the additional option to be stored in all kind of storages in the natural gas grid. Because of high investment costs systems with hydrogen underground tube storage or storage in pressure vessel bundles are not appropriate for long term storage of large volumes.

Table 4: Comparison of large scale storage technologies (Source: LBST, [IfEU 2009], [JRC 2011], [Garche 1999])

Storage technology → / Performance criteria ↓		PHES	CAES	ACAES	Power-to-Gas systems (with re-electrification): E-H_2 – cavern - CCGT (reference) (LBST case example)	E-H_2 – SNG prod. - cavern – CCGT (LBST case example)	Large scale H_2 technologies (literature bandwiths)	E-H_2-underground tubes-FC (LBST case example)	E-H_2-vessel bundles-FC (LBST case example)	Large scale battery storage (Data are based on published literature. Permanent improvements are ongoing.): Lead Acid	Lithium Ion	Sodium Sulphur	Redox Flow
Power rating	[MW]	100-5,000	100-300	100-300	233 MW el. in 650 MW el. out	343 MW el.in 650 MW el. out	0.001+++ (moduls)	8 MW el. in 18.1 MW el. out	0.3 MW el. in 0.7 MW el. out	0.001-50	0.001-50	0.5-50	0.01-10
Energy rating (Charging)	Charge time	1-24h+	1-24h	1-24h	54.5 days	44.5 days	s-24h+++	1.5 days	1.5 days	s - h	s - h	s - h	s - 10h
Response time		s - min	5-15min	5-15min	min	min	min	min	min	ms	ms	ms	ms
Lifetime	years	50-100	30-40[3]	30-40[3]	20	20	5-20	20	20	3-15	5-15	10-15	5-20
System efficiency	%	75-85	42-54	~70	35	24	20-50	28	31	60-95	85-99	85-90	75-85
Investment per power installed[4]	€/kW	750-2,500	400-1,150	>1,200	1,274 el. out	1,824 el. out	550-1,600	4,198 el. out	4,861 el. out	200-650	700-3,000	700-2,000	~2,500
Investment per capacity installed[4]	€/kWh	60-150	10-120	300	8	11	1-15	117	135	100-300	200-1,800	200-900	100-1,000

[3] Not specified if related to above or below-ground technology

[4] Today's costs; application cost can vary; for ACAES: costs are converted from US$ with conversion rate 1 US$ / 0.8 €

In the assessment below, hydrogen underground storage in salt caverns (reference case) is benchmarked with other large scale energy storage concepts.

It clearly shows that only PHES, (A)CAES and large scale Power-to-Gas technologies do have the required power and capacities in order to play a significant role with regard to the integration and large scale storage of increasing amounts of renewable electricity (see Figure 11). In Figure 12, a comparison of the volumetric storage densities of these technologies is depicted.

The storage of chemical energy (H_2 or CH_4) has by far the highest potential. For this reason, H_2/CH_4 are predestined for large scale electricity storage enabling the reliable balancing of long lasting periods with, e.g., low winds in the energy system.

One of the disadvantages of the CH_4 systems is their comparatively low overall efficiency (also influenced by the various potential methods of CO_2 supply / production).

Despite of the low overall system efficiencies, the enhanced development of hydrogen storage systems is highly recommended as it provides the highest volumetric storage capacity compared to other electricity storage technologies such as CAES and PHES, thereby enabling long term storage of electrical energy on a large scale, only paralleled by the use of SNG from Power-to-Gas which is however burdened by other challenges (even lower cycle efficiency, limited long term CO_2-source).

Furthermore, large scale stationary storage of hydrogen enables synergies with both e-mobility by the application of hydrogen powered fuel cell electric vehicles and the direct utilisation of hydrogen in industry.

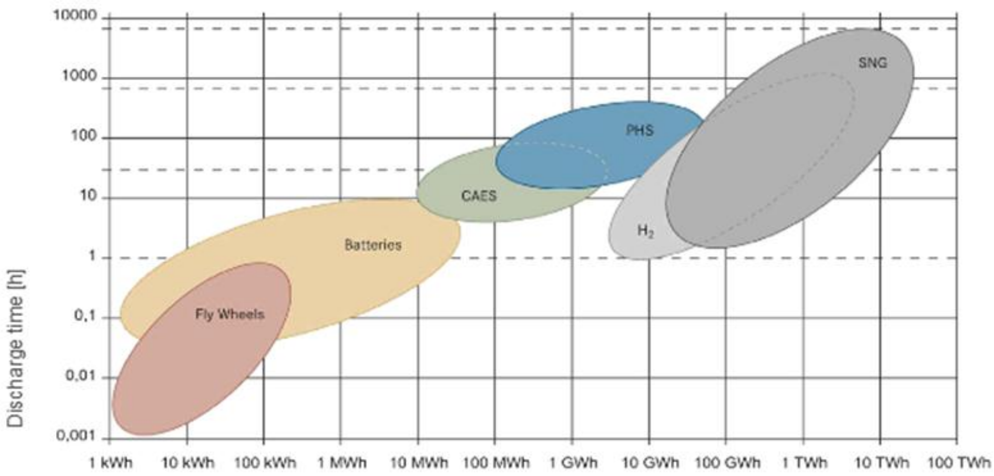
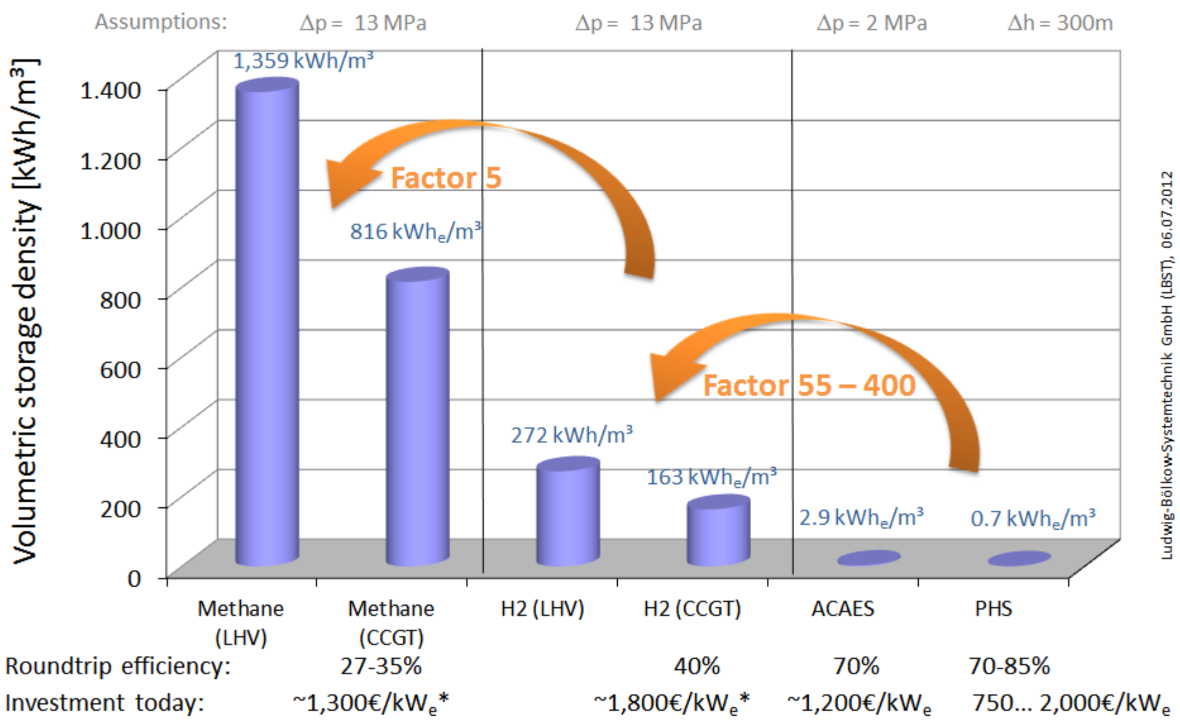


Figure 11: **Assessment of technical storage performance (Source: [Gröschl 2011])**



*Note: assumption: CCGT (60%, 650 MW): 750 €/kW; 7-days storage caverns; methanation (63%): 640 €/kW; electrolysis (60%, 230 MW for H_2, 340 MW for methane): 1,200 €/kW.

Figure 12: Gravimetric and volumetric storage densities, chain efficiency (Source: LBST based on [VDE 2009])

2.4.2 Assessment of storage economics

The storage of electrical energy is always related to significant costs. Large scale storage such as PHES, (A)CAES and Power-to-Gas (H_2 and SNG) requires a large investment with regard to the power installed but they are comparatively cheap with regard to the capacity installed. Figure 13 provides an overview of the relative investments of the electricity storage technologies assessed.

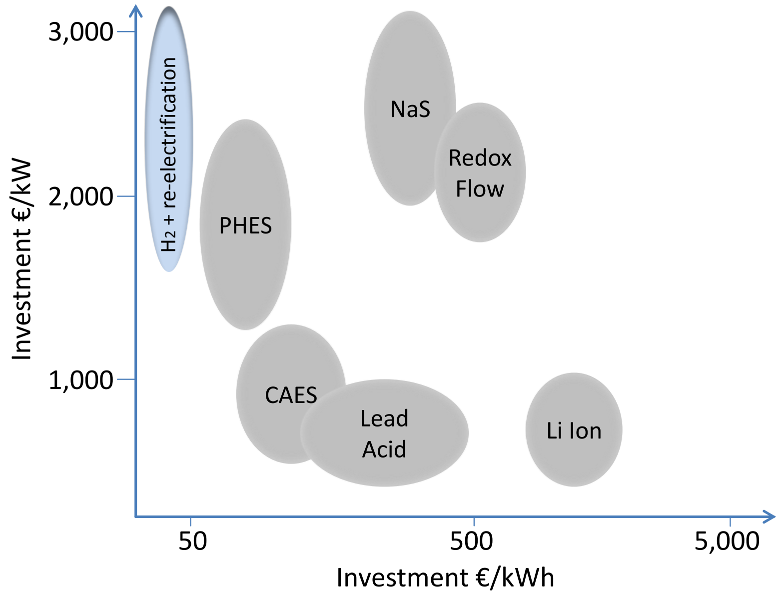


Figure 13: Relative investment for various electricity storage systems (based on [Hotellier 2012])

The broad range of potential usages of hydrogen does not only mean that hydrogen can serve several markets in parallel enabling the exploitation of synergy effects, but also that a diversification of intrinsic business models in line with the reduction of existing market risks can be achieved.

Figure 14 summarizes the achievable prices for hydrogen in different applications. Based on the assumption that hydrogen in the transport sector can be sold in a bandwidth between 6 €/kg_{H_2} (hydrogen delivered to refuelling station) and 8 €/ kg_{H_2} (accepted hydrogen sales price at the refuelling station for end users), it is revealed that hydrogen as a fuel provides the most valuable sales pathway. The other utilisation pathways may, in fact, offer a larger potential in light of volume, but their potential with regard to economic opportunities is clearly below that of the transportation sector.

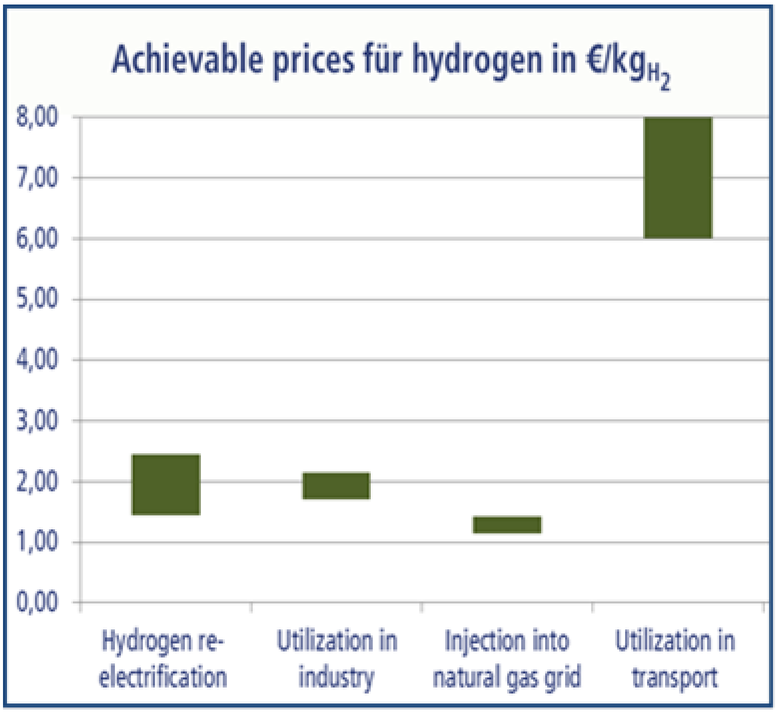


Figure 14: Achievable prices for hydrogen in €/kgH2 (Source: LBST)

The costs of electricity storage depend on several factors – see Figure 15.

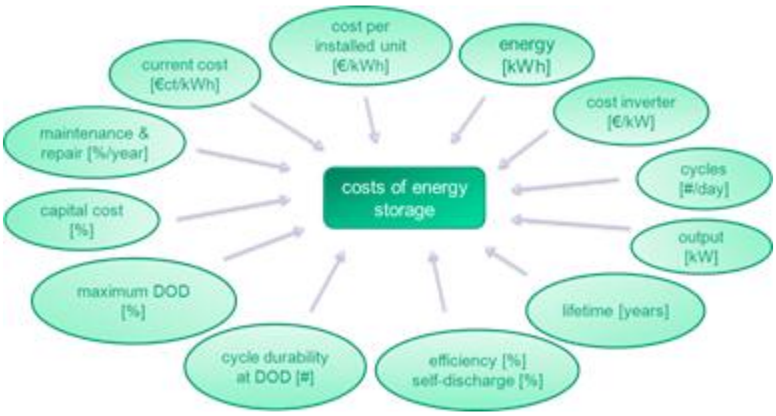


Figure 15: Influential parameters on the costs of energy storage (Source: LBST)

Although the economic viability of hydrogen systems related to today's market conditions is not yet fully given, its potential has been shown to be significant and promising. [VDE 2009] mentions a large potential for cost reductions enabled by series production and technical advancements possibly resulting in halving the full costs of a "week-wise" hydrogen storage system within ten years.

3 Other considerations

Task 2.3, “Other considerations”, will reflect on system constraints in a qualitative fashion concerning availability of scarce resources, regional applicability or industrial / political preferences. In chapter 3.3 a collection of past and on-going projects related to energy storage systems is included. Also the main energy storage system associations are presented.

3.1 *Qualitative system constraints*

Energy storage systems present some qualitative system constraints which might limit their applicability based on certain conditions. Some aspects to be taken into account as well as potential system constraints to be analysed are:

- availability of scarce resources,
- regional applicability of the system; feasibility for different locations or environments,
- industrial / political preferences.

Most of the technologies under consideration require analysing the availability of scarce resources and/or the regional applicability of the systems. PHES facilities are limited in their construction to a feasible topographic area to build the reservoirs.

Furthermore, CAES and hydrogen underground storage are limited by geologic issues, except of pipe storage systems that could be developed almost anywhere. Also other factors such as availability of brine disposal for the leaching of the salt caverns are crucial.

Large scale stationary battery storage systems are not dependent on location parameters or resources. Instead, other parameters that are presented in Table 4 such as the energy rating, lifetime and cost of the battery systems do not allow for the battery technologies to compete in certain applications with the reference technology of HyUnder, the underground storage of hydrogen in salt caverns.

A detailed study on the feasibility and behaviour of certain hydrogen underground storage facilities is presented in Deliverable 3.1 of the HyUnder project, “Overview on all known underground storage technologies for hydrogen”.

Regarding the industrial and political preferences, the support at European level for the development of energy storage systems is presented clearly in the chapter 2.1 of the present report, “European Energy Framework”. The Energy 2020 program: A strategy for competitive, sustainable and secure energy (2020) and the Energy Roadmap 2050 (2050), both the reference plans for the future energy infrastructure in Europe, have among their objectives the development of energy storage systems that enable greater contribution of renewable resources to the energy mix in Europe.

The support of the European Commission for projects like HyUnder through the FCH JU demonstrates this commitment. Also, a large number of players in (the energy) industry have well understood that hydrogen underground storage may play a key role and be one of the key technologies of the future energy system.

At industrial level, the main future users or beneficiaries of the hydrogen underground storage systems seem to be the transport system operators (TSOs) and the gas grid operators. Most of them are already involved in R&D projects regarding energy storage systems or in Power-to-Gas projects. The HyUnder project involves companies from both sectors in the consortium and among its supporting partners.

3.2 *Energy storage associations*

This chapter presents a review of the energy storage associations and projects at European level.

Some energy storage associations have been established in the last years to prepare energy storage solutions in the coming years. At European level, the European Association for Storage of Energy (EASE) is the reference. EASE is a partnership involving mainly energy companies and claims to be the voice of the energy storage community in Europe. The recently established partnership has published its first results in cooperation with the European Energy Research Alliance (EERA) on 14 MAR 2013: “Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap towards 2030” [EASE 2013].

At a world level, the Electricity Storage Association (ESA), has been established in 1991, promoting the development and commercialization of competitive and reliable energy storage systems. Other European member state associations have recently been formed due to the importance of the development of energy storage technologies. In 2012, the German Energy Storage Association (BVES) was established involving more than 30 companies. In the USA, the Department of Energy (DOE) is promoting energy storage programs and performs research and development on a wide variety of storage technologies.

3.3 *Past and on-going projects*

A list of past and on-going projects on energy storage is presented in the following list:

- GROW-DERS: Grid Reliability and Operability with Distributed Generation using Flexible Storage (http://growders.eu/)
- NIGHT WIND: Grid Architecture for Wind Power Production with Energy Storage through load shifting in Refrigerated Warehouses (http://www.nightwind.eu/)

- STORHY: Hydrogen Storage Systems for Automotive Application (http://www.storhy.net/)
- DISTOR: Energy Storage for Direct Steam Solar Power Plants (http://www.dlr.de/tt/desktopdefault.aspx/tabid-2872/4415_read-6488/)
- ALPSTORE: Energy Storage for the Alpine Space (http://www.alpstore.info/)
- NATURALHY: To contribute to the preparation for the hydrogen economy (http://www.naturalhy.net/)
- STORE: Energy storage to allow high penetration of intermittent renewable energy (http://www.store-project.eu/).
- THINK: Energy policies including energy storage (http://www.eui.eu/Projects/THINK/Home.aspx).

Some of the projects have/had their focus on the integration of wind power and hydrogen. Alongside photovoltaics, wind power today is the renewable energy causing most grid management challenges due to its high capacity installed and its intermittency of supply due to the intrinsic characteristics of wind.

4 References

[2009/28/EC] Directive 2009/28/EC of 23 April 2009 on the promotion of the use of energy from renewable sources. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF

[2012/27/EC] Directive 2012/27/EC of the European Parliament and the Council of 25 October 2012 on energy efficiency: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF

[AEUES 2011] Assessment of the required share for stable EU electricity supply until 2050 (AEUES). European Commission, Directorate General for Energy, 2011. http://ec.europa.eu/energy/nuclear/studies/doc/2011_10_electricity_supply.pdf

[arrhenius 2011] arrhenius: Institute for Energy and Climate Policy, Hamburg: Kurzstudie: Die künftige Rolle von Gaskraftwerken in Deutschland; October 2011; http://www.die-klima-allianz.de/wp-content/uploads/2011/10/Klima-Allianz-Studie-Gaskraftwerke-Okt-2011.pdf

[BNetzA 2011] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen: Monitoringbericht 2011

[BNetzA 2012] Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen: Monitoringbericht 2012

[Bouallou 2010] C. Bouallou, J. De Castro, F. Werkoff, "How to improve public perception on hydrogen?", World Hydrogen Energy Conference 2010, Essen, 2010 http://hal-ensmp.archives-ouvertes.fr/docs/00/50/94/18/ANNEX/How_to_improve_the_public_perception_of_hydrogen_presentation.pdf

[Chardon 2010] A. Chardon, Capgermini Consulting, Technology, Outsourcing: Demand Response for electric Mobility, 2010; http://www.vaasaett.com/wp-content/uploads/2010/05/Capgemini-Electric-CarsResponse-for-Electric-Vehicles-V71.pdf [dena 2010] German Energy Agency (dena): power grid study II: Integration Erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015-2020 mit Ausblick 2025, Report, Berlin, 2010

[dena 2012] German Energy Agency (dena): Verteilnetzstudie. Ausbau und Innovationsbedarf der Strom verteilnetze in Deutschland bis 2030. Report, Berlin, 11 December 2012; http://www.dena.de/fileadmin/user_upload/Projekte/Energiesysteme/Dokumente/denaVNS_Abschlussbericht.pdf

[Donadei 2009] S. Donadei, F. Crotogino, “Energy storage in salt caverns – today and tomorrow”, In 9th World salt symposium, Beijing, China; 04-09 September 2009

[DVGW 2012] Deutscher Verein des Gas- und Wasserfaches e.V.: DVGW erforscht Wasserstofftoleranz der Erdgasinfrastruktur, press releasen 25 September 2012; http://www.dvgw.de/presse/pressemitteilungen/dvgw-pressemitteilung/meldung/19646/link//95b5b12bac4fd85f51778f3691979f5a/

[EASE 2013] EASE, EERA: “Joint EASE/EERA recommendations for a European Energy Storage Technology Development Roadmap towards 2030”, 2013 http://www.ease-storage.eu/tl_files/ease-documents/Events/2013.04.17%20Launch%20EASE_EERA%20Roadmap/Roadmap%20&%20Annex/EASE%20EERA-recommendations-Roadmap-LR.pdf

[ECESI 2010] As evidenced by the Commission's Energy Sector Inquiry (ECESI), Communication from the Commission of 1 January 2007 Inquiry pursuant to Article 17 of Regulation (EC)No 1/2003 into the European gas and electricity sectors - COM(2006) 851 - and the high number of investigations into anti-competitive behaviour in the sector (e.g. IP/10/494 of 4 May 2010) http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0851:FIN:EN:PDF

[ECTOS 2004] Ecological City Transport System (ECTOS), “Bringing hydrogen closer to the public”, 2004 http://ec.europa.eu/research/energy/pdf/efchp_hydrogen16.pdf

[EFZN 2011] Energie-Forschungszentrum Niedersachsen: Windenergiespeicherung durch Nachnutzung stillgelegter Bergwerke, report, 2011. http://www.psw.efzn.de/abschlussbericht/ , http://www.gbv.de/dms/clausthal/E_BOOKS/2011/2011EB1130.pdf

[EIP 2010] Energy infrastructure priorities for 2020 and beyond – A Blueprint for integrated European energy network (EIP). European Commission, COM(2010) 677 final, 2010. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SPLIT_COM:2010:0677%2801%29:FIN:EN:PDF

[EIT 2011] Connecting Europe. The Energy Infrastructure of Tomorrow (EIT). European Commission, Energy, 2011. http://ec.europa.eu/energy/mff/facility/doc/2012/connecting-europe.pdf

[EPRI 2011] Electric Power Research Institute (EPRI), D. Rastler: Energy Storage Technology Status, EPRI Renewable Council Meeting, 5-6 April 2011 http://mydocs.epri.com/docs/publicmeetingmaterials/1104/4ANZGWRJTYQ/E236208_02._Rastler_Energy_Storage_Technology_Status.pdf

[ER2050 2011] Energy Roadmap 2050 (ER2050). European Commission, COM(2011) 885/2, 2011. http://ec.europa.eu/energy/energy2020/roadmap/doc/com_2011_8852_en.pdf

[EREN 2012] European Renewable Energy Network, Study, LBST, Hinicio, Centre for European Policy Studies, Technical Research Centre of Finland, January 2012

[ES2020 2010] Energy 2020. A strategy for competitive, sustainable and secure energy (ES2020). European Commission, COM(2010) 639 final, 2010. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:0639:FIN:EN:PDF

[EU 2013] European Commission, DG ENER: Working Paper “The future role and challenges of Energy Storage”, 23 JAN 2013

[EUEF 2012] EU Energy in figures, Statistical pocketbook 2012(EUEF). European Commission, Statistics & Market observatory, 2012. http://ec.europa.eu/energy/observatory/statistics/statistics_en.htm

[EUET2030 2011] EU energy trends to 2030 – Update 2009 (EUET2030). European Commission, Directorate General for Energy in collaboration with Climate Action DG and Mobility and Transport DG, 2011.

http://ec.europa.eu/energy/observatory/trends_2030/doc/trends_to_2030_update_2009.pdf
www.hse.gov.uk/research/rrpdf/rr605.pdf

[FRCES 2013] The Future Role and Challenges of Energy Storage (FRCES). European Commission, Directorate General for Energy, 2013. http://ec.europa.eu/energy/infrastructure/doc/energy-storage/2013/energy_storage.pdf

[Garche 1999] Elektrochemische Speichersysteme für regenerative Energieversorgungsanlagen, Berlin, Dezember 1999

[GERG 2013] GERG project proposal: Hydrogen in the natural gas system Klaus Altfeld, E.ON Ruhrgas AG, October 2011; http://gerg.dgc.eu/activities/board/Power_Gas_%20Essen_Altfeld.pdf, http://www.dbi-gti.de/fileadmin/downloads/5_Veroeffentlichungen/Tagungen_Workshops/2012/H2-FF_2012/12_M%C3%BCller-Syring_DBI.pdf ; http://gerg.dgc.eu/activities/power_hydrogen.htm

[Gravitypower 2013] Company website: http://www.gravitypower.net

[Gröschl 2011] Frank Gröschl: Power to Gas: Innovation for the Gas Infrastructure and Gas Technology, DVGW, Bonn http://gerg.dgc.eu/activities/board/Power_Gas_%20Essen_Groschl.pdf

[GTAI 2011] Germany Trade and Invest - Gesellschaft für Außenwirtschaft und Standortmarketing mbH, Internationale Märkte: Niederlande fahren bei Elektromobilität voran, 07 March 2011; http://www.gtai.de/GTAI/Navigation/DE/Trade/maerkte,did=80322.html

[Heide 2010] H. Heide, M. Greiner, L. Von Bremen, C. Hoffmann, M. Speckmann, S. Bofinger, “Seasonal optimal mix of wind and solar power in a future highly renewable Europe“, Renewable Energy (2011), doi:10.1016/j.renene.2010,03.023, 2010 http://www.sciencedirect.com/science/article/pii/S0960148110001291

[Heide 2011] H. Heide, M. Greiner, L. Von Bremen, C. Hoffmann, “Reduced storage and balancing needs in a fully renewable European power system with excess wind and solar power generation“, Renewable Energy (2010), doi:10.1016/j.renene.2011,02.009, 2011, http://www.sciencedirect.com/science/article/pii/S0960148111000851

[Heineman 2011] B. Heineman, ETH Zurich: The Green Battery of Europe, Balancing renewable energy with Norwegian hydro power, 20 April 2011; http://www.files.ethz.ch/cepe/Top10/Heineman.pdf

[Hickson 2007] A. Hickson, A. Phillips, G. Morales, "Public perception related to a hydrogen hybrid internal combustion engine transit bus demonstration and hydrogen fuel", Energy Policy (2007), doi.org/10.1016/j.enpol.2006.08.002, 2007 http://www.sciencedirect.com/science/article/pii/S0301421506003144

[Hotellier 2012] G. Hotellier (Head of Hydrogen Solutions), Siemens Industry Drive Technologies Hydrogen Solutions: Wasserstoff als Energiespeicher – Potenziale und Umsetzungsszenarien, Nidersächsisches Forum für Energiespeicher, 28 November 2012, Hannover http://www.energiespeicher-nds.de/fileadmin/Events/Forum_EspSys/2012/Vortraege/2012_Forum_EspSys_Hotellier.pdf

[ICCT 2012] The international Council on clean Transportation (ICCT). Ed Pike, P.E.: International Perspective on Electric Vehicles, August 2012; http://chargedsv.org/wp-content/uploads/2012/08/Pike-SAP-final-8-21-2012.pdf

[IEA 2010] International Energy Agency (IEA), Shin-ichi Inage: Working Paper Modelling Load Shifting Using Electric Vehicles in a Smart Grid Environment, 2010 http://www.oecd-ilibrary.org/docserver/download/5km7v0bsmw7k.pdf?expires=1360759937&id=id&accnam

[IES 2011] IEC Market Strategy Board, with a major contribution from the Fraunhofer Institut für Solare Energiesysteme: Electrical Energy Storage, White paper, December 2011 http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

[IfEU 2009] Institut für Energie und Umweltforschung, Heidelberg GmbH "Kurzgutachten Wasserstoff- und Stromspeicher in einem Energiesystem mit hohen Anteilen erneuerbarer Energien: Analyse der kurz- und mittelfristigen Perspektive" Heidelberg, 2009

[JRC 2011] Institute for Energy and Transport (JRC): "2011 Technology Map of the European Strategic Energy Technology Plan (SET-Plan)

	Technology Descriptions", European Union, 2011. http://setis.ec.europa.eu/about-setis/technology-map/2011_Technology_Map1.pdf
[Lightsail 2013]	LightSailEnergy, CA, website: http://lightsailenergy.com/tech.html
[Limberg AT 2013]	PHES Limberg, Austria: www.wiwi.europa-uni.de/de/lehrstuhl/fine/mikro/bilder_und_pdf-dateien/SS10/VLEnergie/Praesentationen/PumpspeicherwerkEL.pdf)
[LRI 2010]	London Research Institute, "Survey of energy storage options in Europe Report", March 2010
[Maack 2005]	M. Maack, J.B. Skulason, "Implementing the hydrogen economy", Journal of Cleaner production (2006), doi.org/10.1016/j.jclepro.2005.05.027, 2005 http://www.sciencedirect.com/science/article/pii/S0959652605001344
[O'Garra 2005]	T. O'Garra, S. Mourato, P. Pearson, "Analysing awareness and acceptability of hydrogen vehicles: A London case study", International Journal of Hydrogen Energy (2005), doi.org/10.1016/j.ijhydene.2004.10.008, 2005 http://www.sciencedirect.com/science/article/pii/S0360319904003350
[Prestat 2010]	B. Prestat, "The Economics of Energy Storage in Electricity Markets. An EDF Perspective", ENARD Workshop, September 2010.
[RWE 2012]	P. Moser, "Zentrale stationäre Energiespeicher – Werkzeug zur Flexibilisierung der Stromerzeugung", EnergieSpeicherSymposium DLR, Stuttgart, 07 MAR 2012 http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/ess_2012/Moser_Zentrale_station_re_Energiespeicher.pdf
[RWE 2013]	RWE Corporate Website: Project ADELE: http://www.rwe.com/web/cms/en/365478/rwe/innovation/projects-technologies/energy-storage/project-adele/
[RWE 2013a]	Personal communication with RWE, Roland Marquardt, on 12 AUG 2013
[Salah 2012]	F. Salah, H. Basse, J. Ilg: Electric Vehicles: Impact on the Utilization of Power Grids in different pricing Scenarios, VDE Kongress 2012 "Smart Grid", Stuttgart, 05-06 November 2012
[Sharp 2009]	J. Sharp, M. Jaccard, D. Keith, "Anticipating public attitudes toward underground CO2 storage", International Journal of Greenhouse Gas Control, doi.org/10.1016/j.ijggc.2009.04.001

http://www.sciencedirect.com/science/article/pii/S1750583609000395

[STORE2.3 2012] Store Project. Facilitating energy storage to allow high penetration of intermittent renewable energy. Deliverable 2.3. “Contribution of Bulk Energy Storage in Future Electricity Systems Facilitating Renewable Energy Expansion” http://www.store-project.eu/en_GB/project-results

[SunFire 2013] company website, technology description: http://www.sunfire.de/kreislauf/power-to-liquids

[SUSPLAN 2011] PLANning for SUStainability, EU-project 2008-2011: Efficient integration of renewable energy into future energy systems, Development of European energy infrastructures in the period 2030 to 2050; www.susplan.eu

[SustainX 2013] SustainX website: http://www.sustainx.com/technology-isothermal-caes.htm

[THINKT8 2012] THINK Project. Topic 8. “Electricity Storage: How to Facilitate its Deployment and Operation in the EU”. http://www.eui.eu/Projects/THINK/Documents/Thinktopic/THINKTopic8online.pdf

[Tokushige 2004] K. Tokushige, K. Akimoto, M. Uno, T. Tomodo, “Evaluation of risk perception and public acceptance of CO2 underground storage by factor analysis”, International Journal of Greenhouse Gas Control, doi.org/10.1016/B978-008044704-9/50359-1 http://www.sciencedirect.com/science/article/pii/B9780080447049503591

[TYNDP 2012] Ten-Year Network Development Plan (TYNDP) 2012, European Network of Transmission System Operators for Electricity, 2012 https://www.entsoe.eu/major-projects/ten-year-network-development-plan/tyndp-2012/

[VDE 2012] Verband der Elektrotechnik Elektronik Informationstechnik (VDE), ETG-Task Force: Demand Side Management: Ein notwendiger Baustein der Energiewende: Demand Side Integration, Lastverschiebungspotenziale in Deutschland, Studie der Energietechnischen Gesellschaft im VDE (ETG), Frankfurt am Main, June 2012

[VDE 2012a] Verband der Elektrotechnik Elektronik Informationstechnik (VDE): Erneuerbare Energie braucht flexible Kraftwerke, Studie der Energietechnischen Gesellschaft im VDE (ETG), Frankfurt am Main, April 2012

[Waidhas 2011] Waidhas, M.; Farchmin, F. (Siemens AG), PEM-Elektrolyse-System als dynamische Komponente für Regelenergie, Erlangen, 05 May 2011

[Wolf 2011] D. Wolf, M. Budt, H.-J. Prümper: Low-temperature Adiabatic Compressed Air Energy Storage; International Renewable Energy Storage Conference and Exhibition (IRES), Berlin, 2011. http://publica.fraunhofer.de/eprints/urn:nbn:de:0011-n-1923277.pdf

[Wurster 2004] R. Wurster, M. Altmann, P. Schmidt, T. O'Garra, S. Mourato, L. Garrity, S. Whitehouse, C. Graesel. A. Beerenwinkel, "Public Acceptance and Economic Preferences Related to Hydrogen Transport Technologies in Five Countries", 15th World Hydrogen Energy Conference 2004, Yokohama, Japan, 27 June- 2 July 2004 http://www.accepth2.com/results/docs/AcceptH2_WHEC15_LBST_JUN2004_presentation.pdf

[Zanter 2011] ZANTER.CONSULTANTS, 42929 Wermelskirchen, Germany, News week 25, year 2011 http://handel.zanter.de/newsdetail/items/bis-zu-2000-meter-unter-dem-meer-betonhohlkugel-energiespeicher-arbeiten-nach-dem-prinzip-von-speicherkraftwerken-probeanlage-so.html

[Zimmer 2010] R. Zimmer, "Acceptance of Hydrogen Technologies and the Role of Trust", World Hydrogen Energy Conference 2010, Essen, 2010 http://www.hytrust.de/fileadmin/download/Zimmer_Essen_18.05.2010.pdf

5 Annexes

5.1 *Energy supply in the EU*

Although European energy generation is still dependent on fossil fuels to a large extent, a new trend in the energy supply could be observed in the EU since 1990. The increase in the share of renewable energy generation and nuclear power becomes visible in Figure 16, especially the increase of the total generation with renewable energy. Nuclear power has stabilized or even decreased its share in the electricity production mix in Europe since 2006.

A decrease in the consumption of fossil fuels since 1990 is also visible and it is especially obvious in the use of solid fuels. Furthermore, also the petroleum and products of petroleum have reduced their share in the primary energy supply.

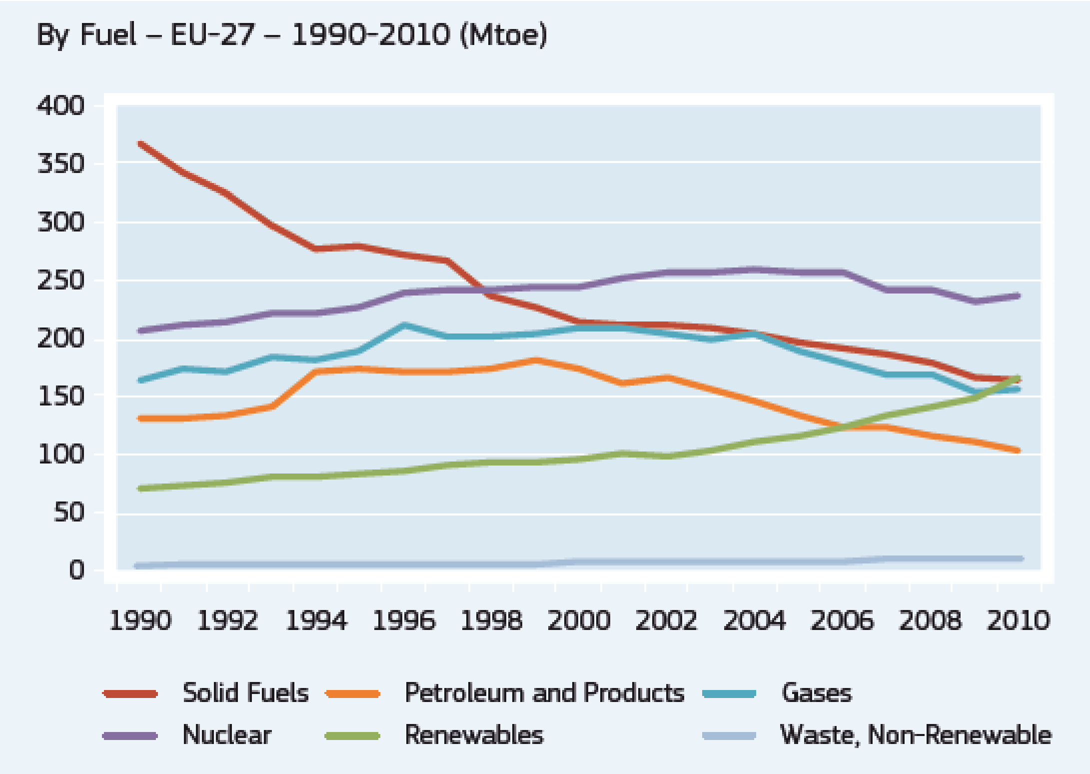


Figure 16: European energy generation by fuel, 1990 – 2010 (Mtoe) (Source: [EUEF 2012])

Since 1990 to 2010 the gross inland energy consumption has remained stable, as it is depicted in Figure 17.

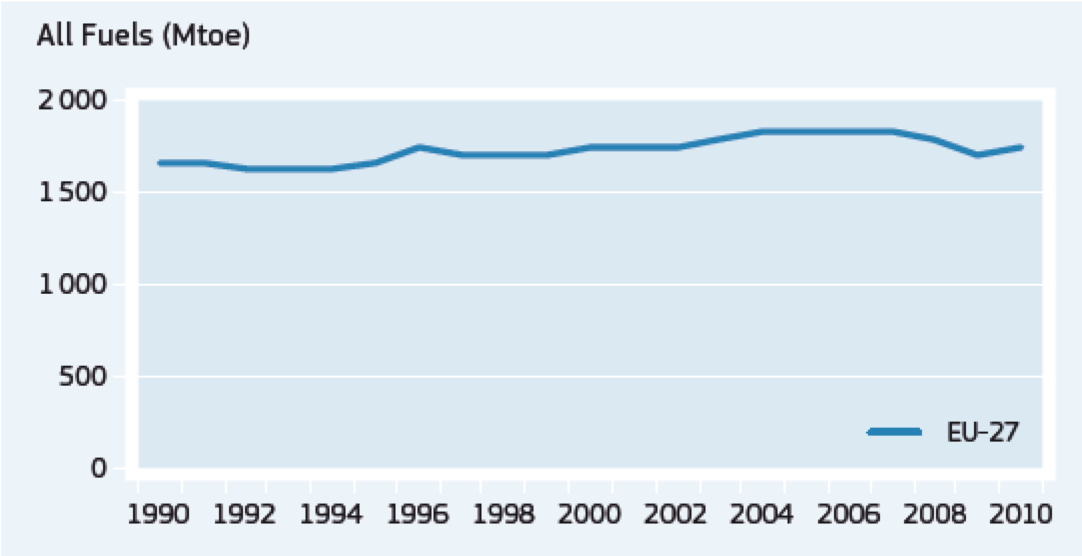


Figure 17: Gross inland energy consumption, 1990 – 2012 (Source: [EUEF 2012])

The development trends for European electricity generation resemble the trend in the global energy mix. The share of, and therefore dependency on, fossil fuels is still high. As can be seen from Figure 18, the main increase during the period analysed (1990 – 2010) is in the development of renewable energy and natural gas.

The use of natural gas has been stable for the same period in the energy mix. Its role in electricity generation has risen due to its increased use for electricity generation in some European countries and due to the higher efficiency of the latest generation of natural gas plants (combined cycle power plants).

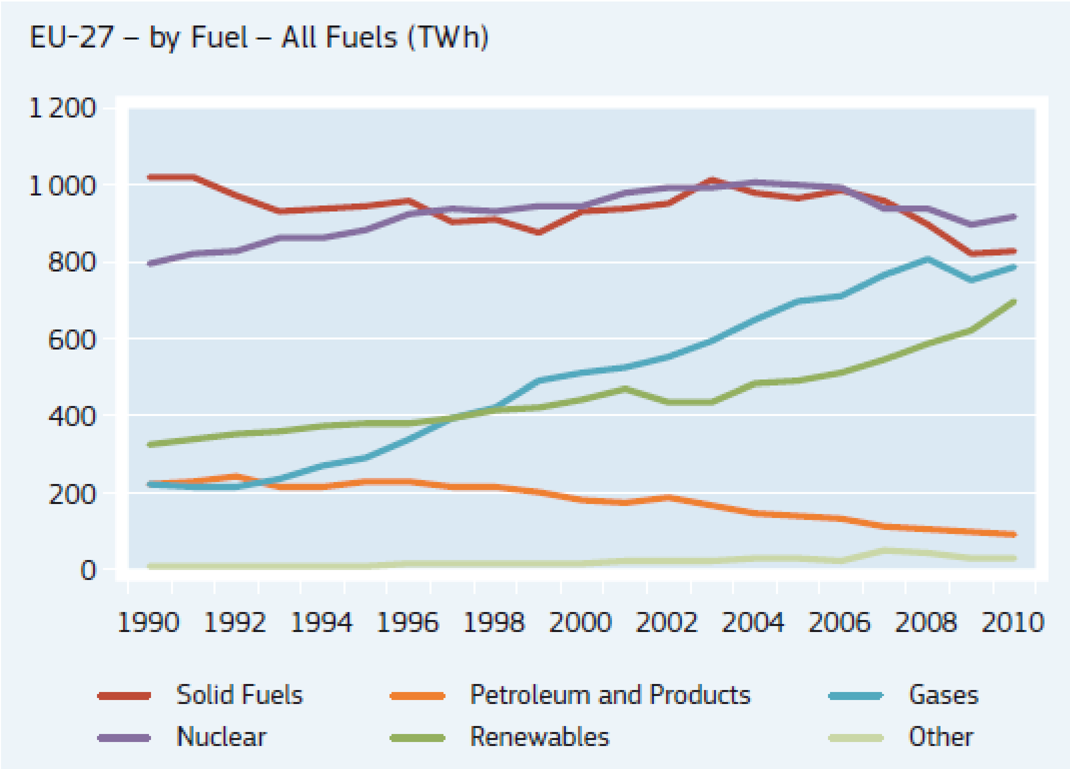


Figure 18: Gross electricity generation in the EU by fuel, 1990 - 2010 (TWh) (Source: [EUEF 2012])

5.2 *Priority electricity, gas and oil corridors in EU 2020*

Infrastructure priorities for the EC comprise the development of electricity, gas and oil corridors. Electricity corridors could play a key role in the management and increase of renewable energy generation. Gas corridors increase the interest in Power-to-Gas projects. The priorities could be seen in Figure 19.

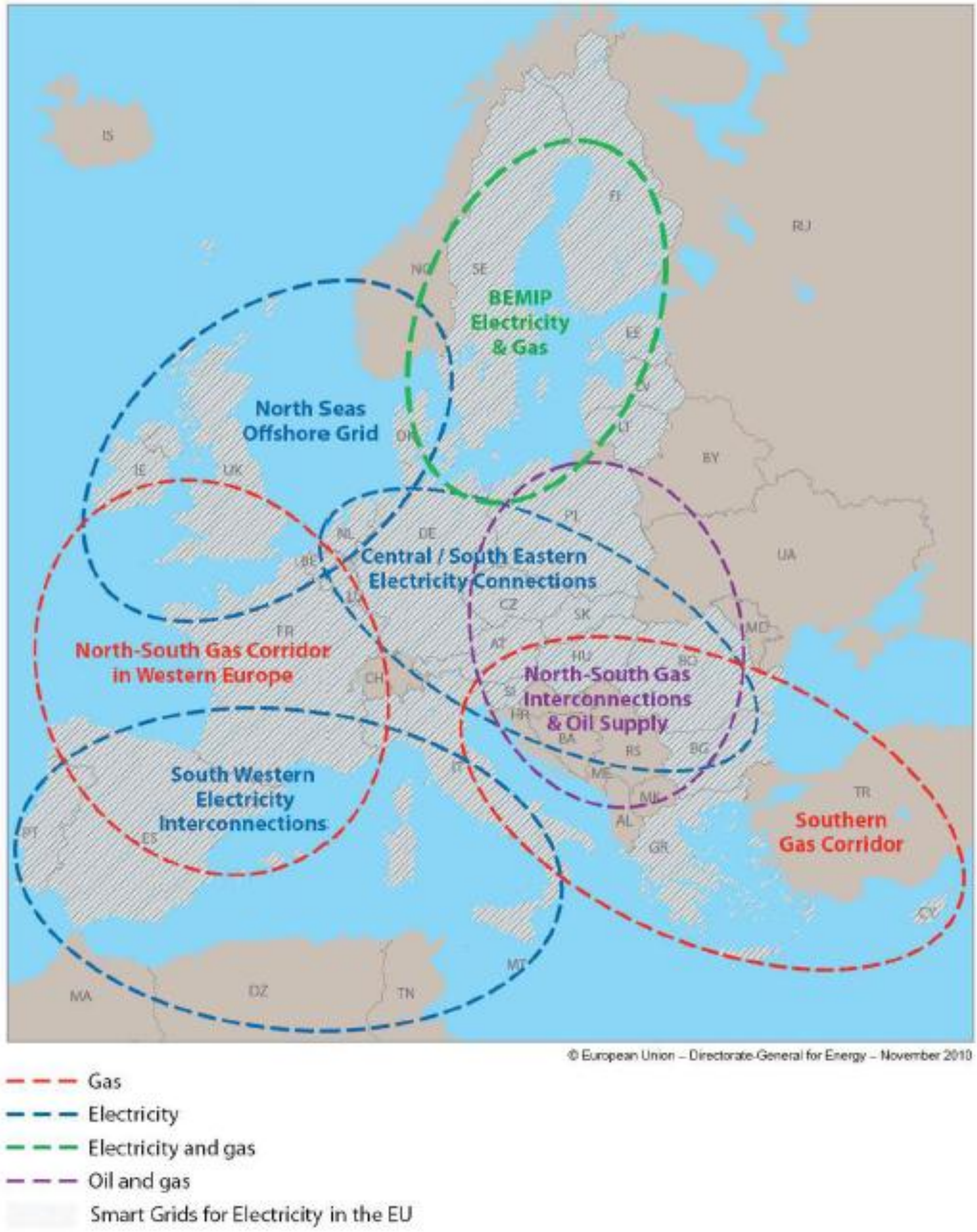
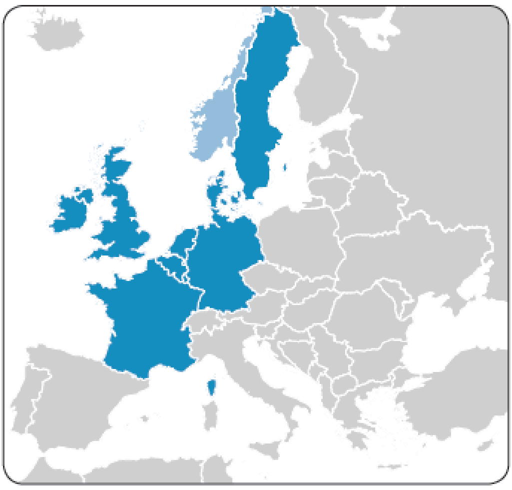


Figure 19: Priority corridors for electricity, gas and oil (Source: [EIP 2010])

The new infrastructures must be taken into account for the HyUnder project assessments. The different HyUnder case studies will be affected by future energy infrastructures. Electrical corridors seem to be an option to increase the integration of renewable energy resources in Europe, the same way as energy storage. Gas corridors will allow an increase in the security of supply (natural gas supply crisis 2009) and will motivate ambitious international projects based on Power-to-Gas technologies and hydrogen underground storage.

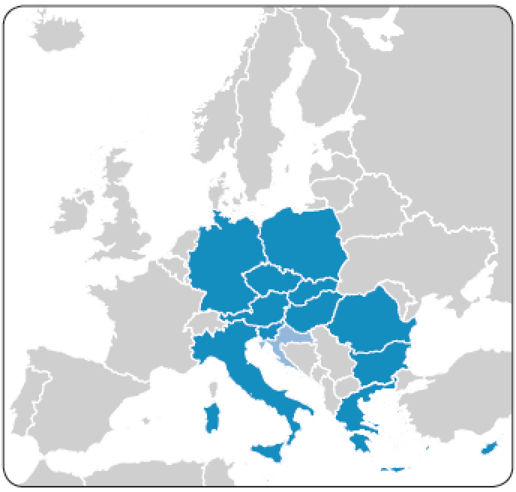
In the following paragraphs, the different HyUnder cases are presented country by country: Germany, France, United Kingdom, The Netherlands, Romania and Spain.

The German case study must take into account the North Sea offshore grid (see Figure 20). This grid will allow the integration and connection of the renewable energy production in the North Sea (up to 22 GW of offshore wind energy is planned in the North Sea). The grid could connect the large electricity generation and consumption centres in the North Sea and Central – Northern Europe respectively, with energy storage by pumped hydro energy storage facilities in the Alpine region and in Norway. The German case must be affected also by the North – South electricity interconnections in Central and South Eastern Europe, see Figure 21, by the North – South gas corridors, see Figure 22 and Figure 23, and by the BEMIP (Baltic Energy Market Interconnection Plan) to some lesser extent (Figure 21). The "Energiewende" has made Germany to become the European / World showcase to live-test the introduction of REN in very short time with ample time for testing, posing chances and risks simultaneously.



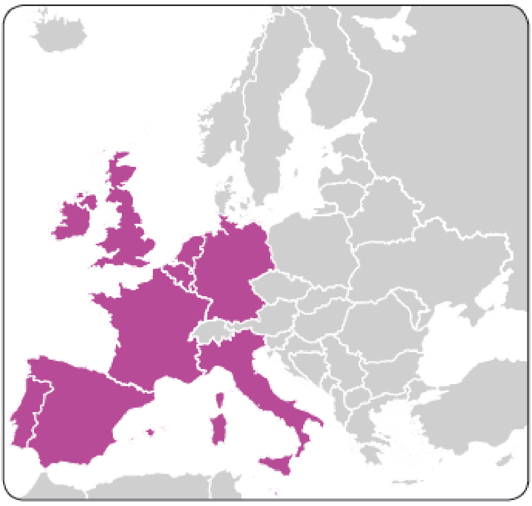
Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between Denmark and the Netherlands
New sub-sea interconnector between France and the UK
New sub-sea interconnector between the UK and Belgium
Sub-sea interconnector and hub between Germany/ UK and Norway[6]
AC land link between Northern and Southern Ireland

Figure 20: North Sea offshore grid (Source: [EIT 2011])



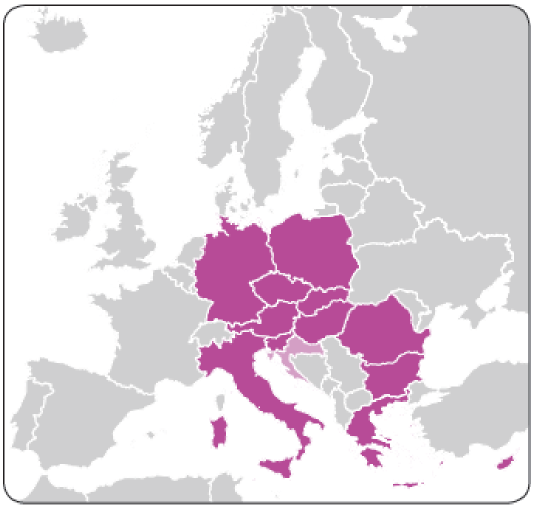
Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between Hungary and Slovakia
New interconnection between Germany and the Czech Republic
New interconnection between Slovenia and Italy
Interconnection upgrade between Bulgaria and Romania, and Bulgaria and Greece
Capacity increases between Germany and Austria, and Poland and Germany
Capacity increase between Slovenia and Hungary/ Croatia[8]
Strengthening of North-South infrastructure within Germany

Figure 21: North – South electricity interconnections in Central Eastern and South Eastern Europe (Source: [EIT 2011])



Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between the UK and Ireland
New interconnections between France and Belgium, and France and Luxembourg
MIDCAT, a new interconnection between France and Spain
Third new interconnection between Portugal and Spain
Interconnection upgrade between Germany and Austria
Interconnection upgrade between Italy and Malta
Interconnection upgrades between France, Italy, Belgium and Germany

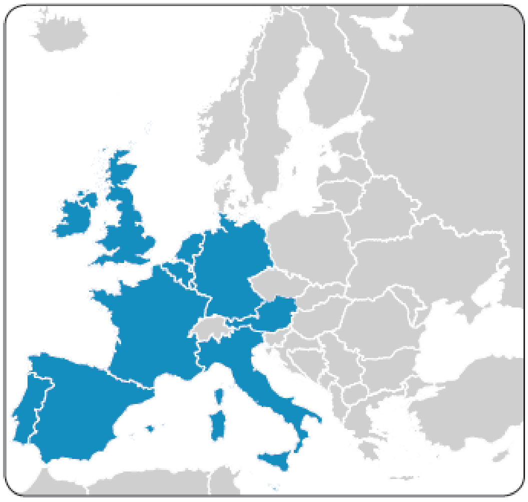
Figure 22: North-South gas interconnections in Western Europe (Source: [EIT 2011])



Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between Slovakia and Hungary
Interconnections linking Slovenia, Italy and Austria
Interconnection upgrades between Czech Republic and Poland
New LNG regasification terminal in Croatia[10]
Reverse flow upgrades between Bulgaria and Romania, Hungary and Romania and Bulgaria and Greece

Figure 23: North-South gas interconnections in Central Eastern and South Eastern Europe (Source: [EIT 2011])

The French case study is affected by the North Sea offshore grid, see Figure 20, the North-South gas interconnections in Western Europe, see Figure 22 and the South Western electricity interconnections, see Figure 24. The South Western electricity interconnections will allow a better accommodation of RES among the Iberian Peninsula and France, further connecting with Central Europe and an interconnection between North Africa RES and Europe.



Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between Spain and Portugal
New interconnection between France and Spain
New interconnection and upgrade of existing capacity between Germany and Belgium
New underground and subsea interconnection between Ireland and the UK
New interconnection and an upgrade of existing capacity between Italy and Austria[7]
New double line interconnection between Germany and the Netherlands
Upgrade of an interconnection between France and Italy

Figure 24: North – South electricity interconnections in Western Europe (Source: [EIT 2011])

Also the Dutch case study will be affected by the North Sea offshore grid, see Figure 20, and by the North – South gas corridors, see Figure 22 and Figure 23.

The Spanish case study will be affected by the South Western electricity interconnections, see Figure 24, and by the North-South gas interconnections in Western Europe, see Figure 22.

The UK case study will be affected by the North Seas offshore grid, see Figure 20, and by the North-South gas interconnections in Western Europe, see Figure 22.

The Romanian case study is affected North-South gas interconnections in Central Eastern and South Eastern Europe, see Figure 23, by the North – South electricity interconnections in Central Eastern and South Eastern Europe, see Figure 21, and by the Southern Gas Corridor, see Figure 25. The Southern Gas Corridor will increase security of supply in the region and will allow Power–to–Gas initiatives.

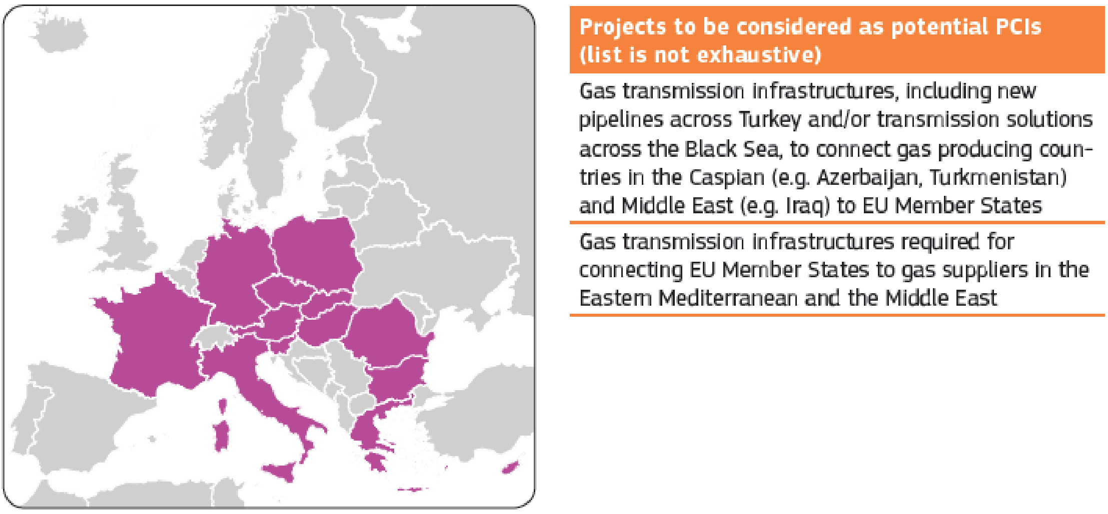


Figure 25: Southern Gas Corridor (Source: [EIT 2011])

5.3 *Energy Roadmap 2050 scenarios*

This chapter contains a brief overview of the scenarios and hypothesis assumed by the Energy Roadmap 2050 underlying its assessment:

Table 5: Overview of scenarios for the Energy Roadmap 2050 (Source: [ER2050 2011])

Overview of scenarios[12]

Current trend scenarios

- Reference scenario. The Reference scenario includes current trends and long-term projections on economic development (gross domestic product (GDP) growth 1.7% pa). The scenario includes policies adopted by March 2010, including the 2020 targets for RES share and GHG reductions as well as the Emissions Trading Scheme (ETS) Directive. For the analysis, several sensitivities with lower and higher GDP growth rates and lower and higher energy import prices were analysed.

- Current Policy Initiatives (CPI). This scenario updates measures adopted, e.g. after the Fukushima events following the natural disasters in Japan, and being proposed as in the Energy 2020 strategy; the scenario also includes proposed actions concerning the "Energy Efficiency Plan" and the new "Energy Taxation Directive".

Decarbonisation scenarios (see graph 1)

- High Energy Efficiency. Political commitment to very high energy savings; it includes e.g. more stringent minimum requirements for appliances and new buildings; high renovation rates of existing buildings; establishment of energy savings obligations on energy utilities. This leads to a decrease in energy demand of 41% by 2050 as compared to the peaks in 2005-2006.

- Diversified supply technologies. No technology is preferred; all energy sources can compete on a market basis with no specific support measures. Decarbonisation is driven by carbon pricing assuming public acceptance of both nuclear and Carbon Capture & Storage (CCS).

- High Renewable energy sources (RES). Strong support measures for RES leading to a very high share of RES in gross final energy consumption (75% in 2050) and a share of RES in electricity *consumption* reaching 97%.

- Delayed CCS. Similar to Diversified supply technologies scenario but assuming that CCS is delayed, leading to higher shares for nuclear energy with decarbonisation driven by carbon prices rather than technology push.

- Low nuclear. Similar to Diversified supply technologies scenario but assuming that no new nuclear (besides reactors currently under construction) is being built resulting in a higher penetration of CCS (around 32% in power generation).

For details on the scenarios see Impact Assessment:
http://ec.europa.eu/energy/energy2020/roadmap/doc/sec_2011_1565_part2.pdf

5.4 *Natural gas working volume and storage capacity in EU-27*

Some European countries already have natural gas storage installations in order to an enable seasonal management of the resource and to avoid supply problems due to geo – political instabilities in the export countries, listed in the following table.

Table 6: Natural gas volume and storage capacity EU-27 (Source: [FRCES 2013])

	Maximum working volume (million m³)	Maximum withdrawal capacity per day (million m³)	Average days of storage (volume/capacity)
Austria	4744	58	82
Belgium	600	12	50
Bulgaria	600	4	150
Cyprus	0	0	0
Czech Republic	3127	52	60
Denmark	1020	18	57
Estonia	0	0	0
Finland	0	0	0
France	11900	200	60
Germany	21297	515	41
Greece	0	0	0
Hungary	6330	72	88
Ireland	230	3	77
Italy	14747	153	96
Latvia	2325	24	97
Lithuania	0	0	0
Luxembourg	0	0	0
Malta	0	0	0
Netherlands	5000	145	34
Norway			
Poland	1640	32	51
Portugal	159	2	80
Romania	2760	28	99
Slovakia	2785	39	71
Slovenia	0	0	0
Spain	2367	13	182
Sweden	9	1	9
Switzerland	0	0	0
Turkey	2661	18	148
UK	4350	86	
Total EU-27 plus Switzerland, Turkey	**88651**	**1475**	**51**

Courtesy: Eurogas, statistical report 2011

5.5 *Pumped Hydro Electricity Storage*

Table 7: Installed PHES power in Europe [EU 2013, p. 11]

	PHES (MW installed in 2010)	PHES (MW to be newly installed by 2015)
Italy	8,895	
Germany	7,736	74
Spain	5,657	1,270
France	5,229	
Austria	3,774	1,027
UK	3,251	
Switzerland	2,729	1,628
Poland	1,948	
Norway	1,690	
Bulgaria	1,330	
Czech Republic	1,239	
Belgium	1,186	
Luxembourg	1,146	200
Portugal	968	1,660
Slovakia	968	
Lithuania	820	
Greece	729	
Ireland	594	
Turkey	500	
Sweden	466	
Romania	378	
Slovenia	185	
Finland	0	
Netherlands	0	
Denmark	0	
Cyprus	0	
Estonia	0	
Malta	0	
Total EU-27 plus Norway, Switzerland, Turkey	51,008 MW	5,859 MW

5.6 *Supply Side Management*

Table 8: Flexibility of conventional power generation ([VDE 2012a: p. 110 Tab. 8])

	Anfahrzeit h	Mindestlast %	Wirkungsgrad Nennpunkt P_n	Wirkungsgrad bei 50% P_n
stand alo-ne Gas-turbine	< 0,1	20 – 50 %	30 – 35 %	27- 32 %
GuD Standard	0,75-1,0	30 – 50 %	58 – 59 %	54 - 57 %
GuD flexibel	0,5	15 – 25 %	>60 %	52 – 55 %
Steinkohle Standard	2- 3	40	42 – 45 %	40 – 42 %
Steinkohle flexibel	1 - 2	20	45 – 47 %	42 – 44 %