“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

°C	degree Celsius
ACAES	Adiabatic CAES
ARE	Alliance for Rural Electrification
BEV	Battery Electric Vehicle
BGS	British Geological Survey
BVES	German Energy Storage Association
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CH_4	Methane
CHP	Combined Heat and Power
CNESA	China Energy Storage Alliance
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DME	Dimethylether
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
FT	Fischer-Tropsch
GESA	Global Energy Storage Alliance

GHG	Green House Gas(es)
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt-hour
h	hour
H_2	Hydrogen
ICAES	Isothermal CAES
ICE	Internal combustion engine
IESA	India Energy Storage Alliance
kg	kilogram
km	kilometre
kW	kilowatt
kWh	kilowatt-hour
LA	Lead Acid
LAES	Liquid air energy storage
LCC	Last Cemented Casing
LHV	Lower heating value
Li-Ion	Lithium ion
LTA-CAES	Low-Temperature CAES
min	minute
MJ	Megajoule
ms	millisecond
Mtoe	Million Tons of Oil Equivalent
MW	Megawatt
MWh	Megawatt-hour
NaS	Sodium Sulphur
O&M	Operations and maintenance
OPEX	Operational Expenditure
PHES	Pumped Hydro Energy Storage
PHEV	Plug-in Hybrid Electric Vehicle
$PtCH_4$	Power-to-Methane

PtG	Power-to-Gas
PtH_2	Power-to-Hydrogen
PtL	Power-to-Liquid
PV	Photovoltaics
R&D	Research and Development
RCS	Regulations, Codes and Standards
RE	Renewable Energy
RES	Renewable Energy Sources
RON	Research Octane Number
s	second
SMDS	Shell Middle Distillate Synthesis
SOEC	Solid oxide electrolysis cell
SSM	Supply Side Management
ST	Steam turbine
TES	Thermal Energy Storage
TSO	Transport System Operator
TWh	Terawatt-hour
TYNDP	Ten Year Network Development Plan
UK	United Kingdom
USA	United States of America
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 methane,
- hydrogen mixed-in with natural gas or other chemicals (methanol),
- Power-to-Liquid (PtL),
- large scale battery storage,

as well as other grid based structural measures such as

- 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. However, the current discussion around nuclear energy could change its perception as a low cost system. Taking into account additional safety measures, external insurance costs, nuclear waste management disposal cost 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 potential transition fuel. The use of synthetic methane and natural gas – hydrogen mixtures could play an important role in mobility and in power generation as well.

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 might play a role until 2050 in some regions, 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. In addition, underground hydrogen storage will allow to store renewable energy coming from regional and global reliable sources outside Europe (i.e. Patagonia wind resources, Northern Africa solar resources).

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.

The European Commission has not yet 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.

During 2013, and after the submission of the Deliverable 2.1 of the HyUnder project, some advances have been presented in the STORE project related to the quantification of future energy storage requirements in some countries of the EU (Spain, Germany, Denmark, Greece, Austria and Ireland). The results obtained present that, "In 2020 storage needs will strongly depend on the flexibility of the electricity supply system. In scenarios with an REN share > 80% of the net electricity production, additional energy storage facilities are needed" [STORE DE 2013]. One of the main conclusions of the STORE project reports is that without a strong increase in the penetration of intermittent renewable energies PHES systems will be sufficient to manage surplus electricity from RES. For scenarios of 80% share of RES on the net electricity consumption energy storage will be required among other solutions as the optimal share of intermittent RES, wind and solar mainly, seem to be crucial to reduce energy storage needs. In some countries like Germany interconnection capacity would play an important role, where the Austrian PHES has huge capacity to accept surplus from German RES. Therefore, an extension of the existing cross border transmission capacity would be required. Other countries like Spain also have limited interconnection capacity. [STORE DE 2013] [STORE SP 2013].

A quantification of the German energy storage needs is presented in [STORE DE 2013], where for scenarios of 80% share of RES on the net electricity consumption energy storage systems of 950 GWh to 1,534 GWh will be needed, depending on the particular scenario. For comparison, results obtained in the German Case Study of the HyUnder project estimated an energy storage need of 9 TWh (e.g. in the form of hydrogen underground storage). Both studies however use different approaches and methodologies.

Relevant analyses 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 take into account a highly renewable respectively 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 optimum seasonal mix; 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].

According to the 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) a hydrogen storage system with an energy storage capacity of 50 TWh and a discharge power of 220 GW is required (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.

Currently, 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 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 should become prerequisite for planning a greater penetration of RES in the EU energy mix until 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. To date, quantifications of the energy storage needs in the EU have been undertaken only for some countries e.g. under the STORE project framework and, focused on hydrogen underground storage, in the HyUnder project again only for certain EU countries as well as in some scientific articles.

Hydrogen underground storage is a really promising technology due to its high volumetric energy storage density and the fact that hydrogen storage in underground salt caverns is already state of the art. 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 capacity.

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 grid. 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 to the energy supply system. The most relevant complementary technology options to energy storage for the integration of variable renewables are shown in Figure 1:

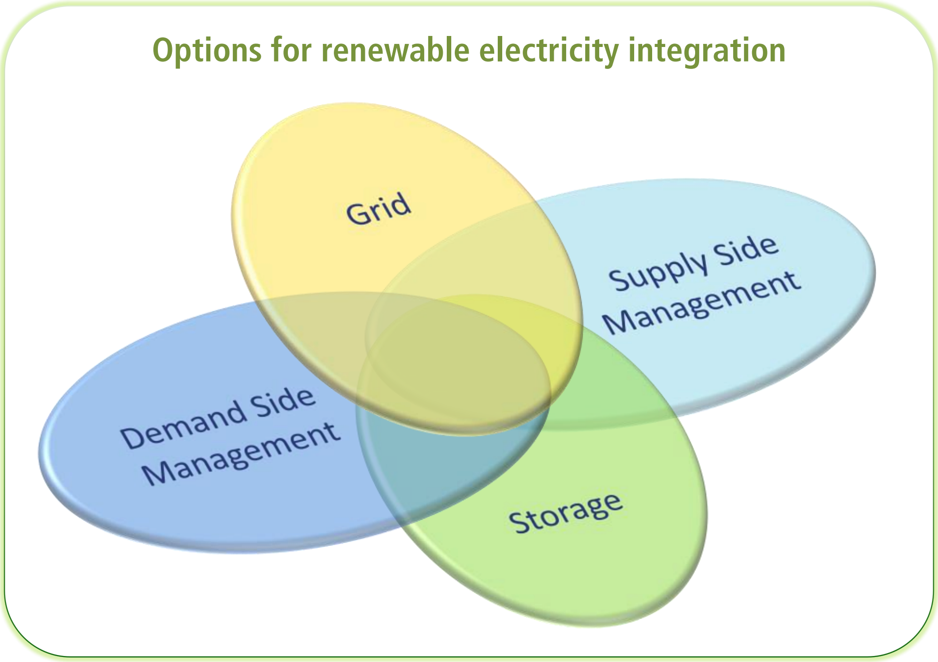


Figure 1: **Options for renewable electricity integration (Source: LBST)**

- 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 provide a universal solution. On a long term only the coordinated interaction between generation, transmission, distribution, storage and consumption of electrical energy will facilitate an effective integration of renewable energy in the power supply system. The above mentioned options hereto 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 appearing in Europe as well as inside the countries and on regional level.

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. Projects of pan-European significance are diverse, adapting to the specific geography they are inserted in. Total investment costs for these projects amount to € 104 billion, of which € 23 billion are for subsea cables [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 the following distribution grid extension requirements (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 short and medium term.

However, unlimited transmission capacity alone will not be sufficient to ensure security of supply in an energy system 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 can contribute to the stabilization of the electricity grid.

Future conventional power plants have to meet the following requirements in order 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.

Power plants have different characteristics, making some of them more suitable for the provision of specific 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.

In a transition phase, 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, synthetic 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. Facilities, those shutdown do 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.

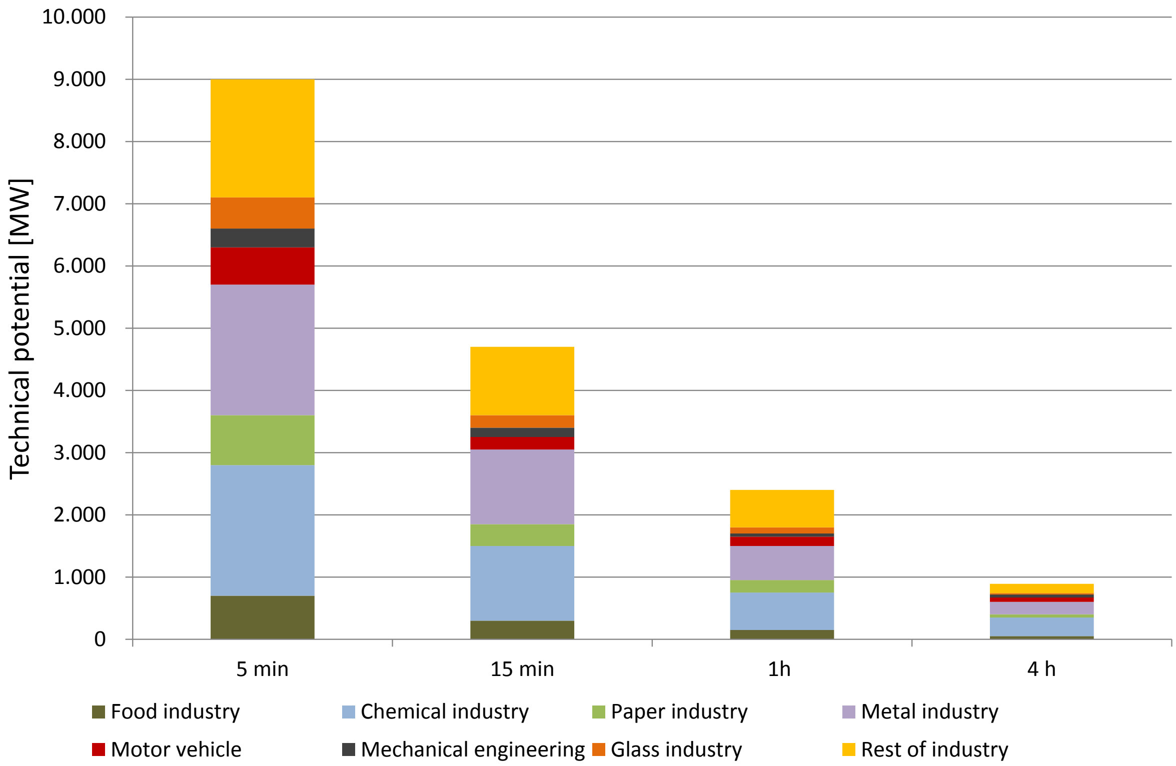


Figure 2: Technical potential of interruptible power for various industry segments related to the shutdown time (Source: LBST based on [FfE 2010])

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 or 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 significantly contribute to a high penetration of renewable electricity. Household refrigerators, washers, dishwashers and dryers are some typical appliances with potential DSM connectivity.

Figure 3: Options for small DSM applications (Source: [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 levels, need for smart meter installations, necessary IT networks, additional infrastructure costs, (data) safety issues, etc. The potential future growth is mainly driven by 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. Furthermore, the forecasted technical potentials for load shifting in households may significantly decrease because of the strong increase of the 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 experiences with DSM exist 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 emerge 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.

The potential utilisation of battery electric vehicles for load shifting (dispatched battery charging) has been widely discussed. The largest bunch of grid services could be provided by the vehicle-to-grid concept (V2G): in this concept the EV can feed back to the grid by discharging the on-board battery.

Table 2: Selection of e-mobility targets (Source: [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 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 functions,
- 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, but 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 over 8 hours[1].

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

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]. The "rush hour of electricity" follows the rush hour in traffic. A suitable charging system communicating with the power networks as well as appropriate electricity tariff structures could contribute to solve 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 further important options 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 (Source: [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 today but can be momentous in 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 remain limited to an hourly level also in the future.

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 maintain grid stability, system black-start capability and local supply security.

In the EU (with Norway, Switzerland and Turkey) about 51 GW of pumped hydro energy storage are in operation today (see Chapter 2.3.1). There is only one European CAES facility with 321 MW installed in Germany (see Chapter 2.3.2). Other storage technologies contribute only minor storage capacities.

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, Power-to-Gas and Power-to-Liquid 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.

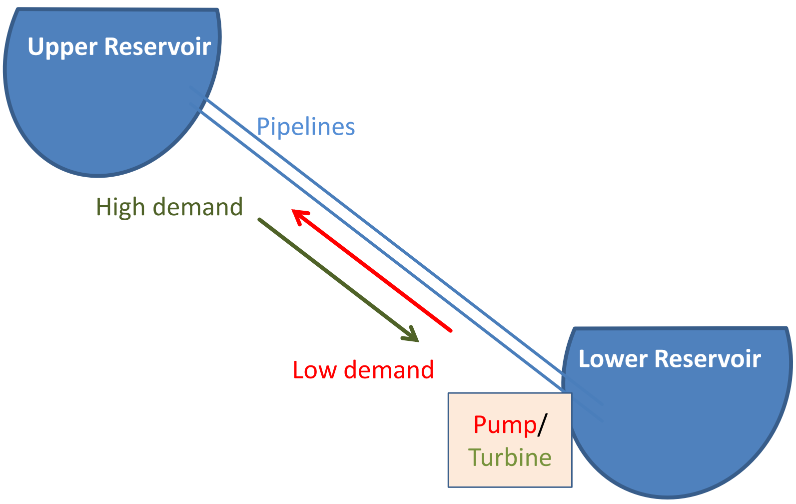


Figure 5: A principle schematic of a PHES plant (Source: LBST)

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 (1-2 min if standing still, 10 sec if spinning). 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) of its non-rotating parts.

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

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.

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 potential for expanding of PHES is limited due to its dependence on topographical conditions and potential environmental impacts. Most of the largest new plants will be constructed in countries with most appropriate topographical conditions (like Switzerland, Spain, Austria or Norway) [ecoprog 2011].

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.

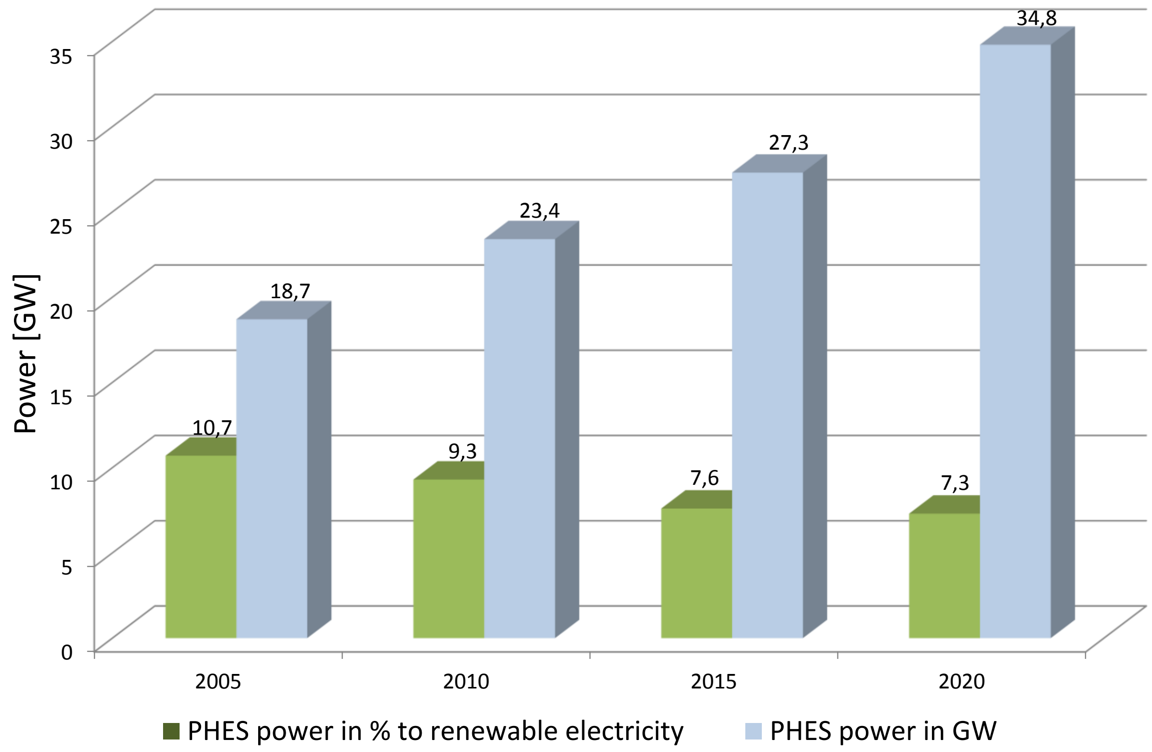


Figure 6: **Development of absolute und relative power of PHES in relation to renewable installations in EU-27 (Source: LBST based on [VDE 2012a])**

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 requirements for the realisation of 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. A first theoretical estimate of the overall potential for Germany resulted in 10 GW power and 40 GWh storage capacity which could be installed [EFZN 2011]. A first small pilot installation for research purposes could be realized not before the 2015 - 2018 time frame [BINE 2013],

- 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.

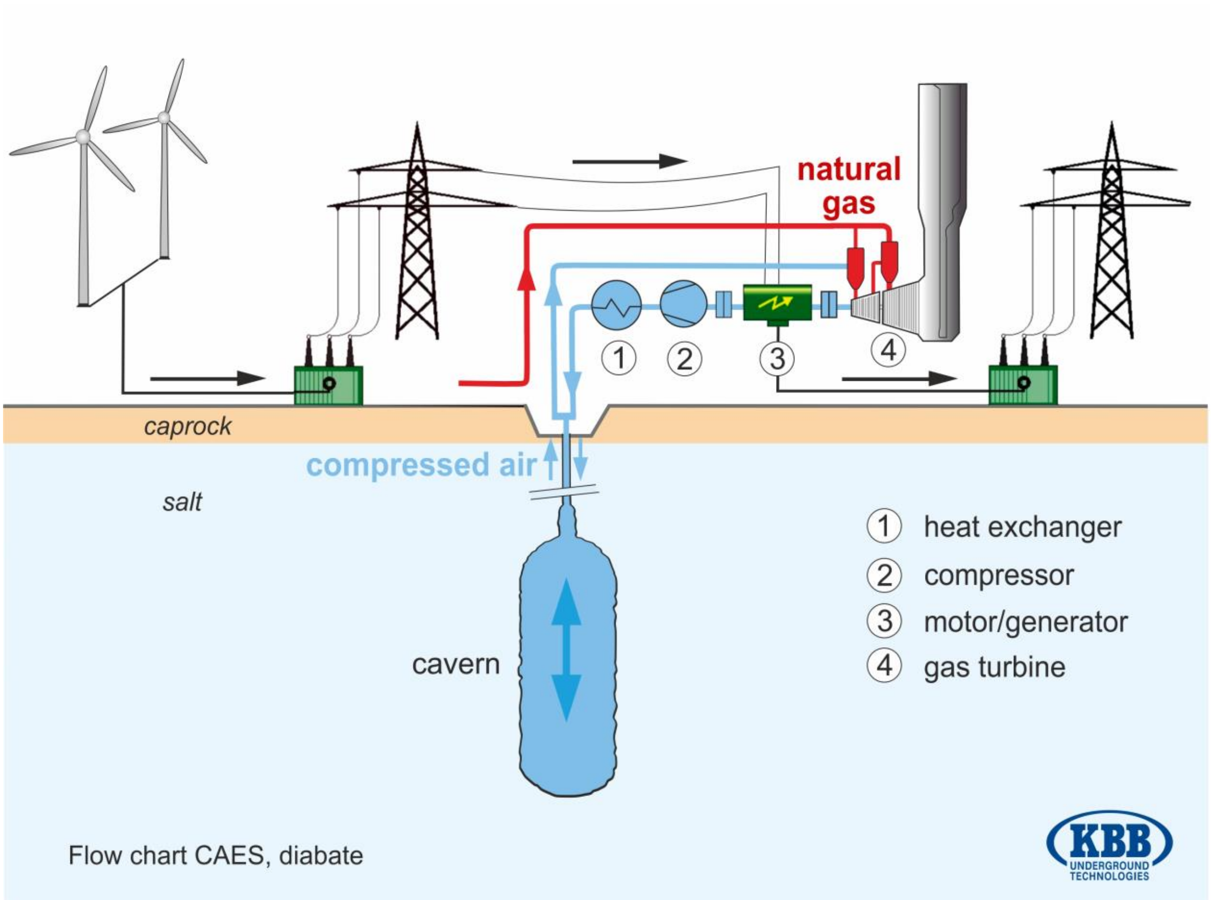


Figure 7: CAES plant with underground storage (Source: KBB Underground Technologies GmbH)

In the EU there is only one CAES facility with a power of 321 MW. The installed power of CAES plants is expected to be 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 30+ years and a cycle lifetime of > 10,000 cycles.

In conventional CAES plants the heat developing during compression needs to be dissipated by cooling and is not stored. Without heat recovery, the round-trip efficiency of diabatic CAES is in the range of 42% (see Table 6), 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 (Source: [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.

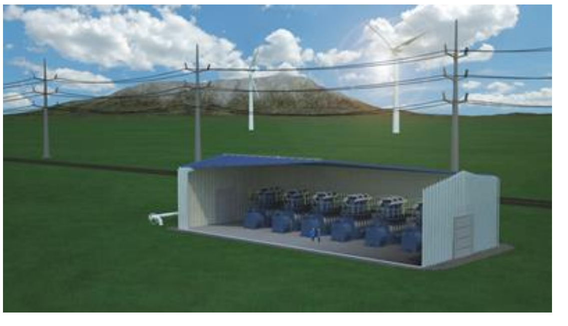


Figure 8: Isothermal compressed air energy storage (Source: [SustainX 2013])

- Regenerative air energy storage: first product of LightSail, California, USA: LightSail RAES-V1 (power 250 kW, capacity 1 MWh, efficiency 70%) [LightSail 2013].
- "Liquid air energy storage (LAES) systems employ proven cryogenic processes that use liquid air as the energy storage instead of compressed air. The LAES systems operate by using electrical energy to drive an air liquefier and storing the resultant liquid air (~ -196 °C) in an insulated tank at atmospheric pressure. To recover the stored energy, the liquid air is released from the storage tank, pumped in its liquid form to high pressure, vaporised and heated to ambient temperature by using either ambient heat or waste heat. The resultant high pressure gaseous air is used to drive an expansion turbine and to generate electricity." [Store2.1 2013, p. 21]

  A long duration energy storage system based on the liquid air cycle has recently been developed by Highview Power Storage and demonstrated at a 300 kW / 2.5 MWh pilot plant in Slough/UK [LAEN 2013]. A 5 MW / 15 MWh pre-commercial demonstration plant is scheduled to be operational by mid 2015 [HPS 2014].

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 electrical energy to chemical energy and convert the stored chemical energy back into electrical energy. A heap of battery technologies and chemistries are known today. Most prominent are lead acid (LA), lithium ion (Li-Ion), sodium sulphur (NaS) and redox-flow batteries. In order to provide larger storage capacities, batteries can be clustered 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 - 20 years) and also the number of charge / discharge cycles is limited (LA: ~500 cycles; NaS: ~4,500 to 10,000 cycles depending on technology, depth of discharge, and further operating parameters). An exemption is the redox-flow battery with two separate electrolyte tanks, where the number of cycles is theoretically not limited and the calendar life simultaneously can be high (> 15 years) [Gildemeister 2013a]. Redox-flow batteries work rather like a fuel cell than a conventional battery e.g. a lead acid battery.

There are battery technologies which are operated at low (25-30°C) temperature (LA, Li-Ion, Redox-Flow) and at high (~300°C) temperature (NaS). Table 4 shows examples for electricity storage based on battery systems for grid stabilisation.

Table 4: Examples for electricity storage based on battery systems for grid stabilisation (Source: [NGK 2013], [Younicos 2014])

	NaS	Li-Ion
Rated power	1 MW	200 kW
Energy	6 MWh	200 kWh
Efficiency	85% DC (~75% AC)	95% DC (85% AC)
Cyclic life	4,500 cycles	4,000 cycles
Calendar life	15 years	20 years
Operation temperature	300°C	ambient
Manufacturer	NGK Insulators Ltd.	Samsung SDI

Battery systems for stationary applications must not be mixed up with battery systems for battery electric vehicles. There is a trade-off between high storage capacity, high power output and high volumetric and gravimetric storage density. For stationary applications space requirements and mass are not as important as in mobile applications. Therefore, the battery systems can be designed for long lifetime and higher space requirements and mass can be accepted.

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 (redox-flow batteries being the most prominent representative of this battery group) 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.

Battery systems in combination with power electronics can be reasonably used for the provision of grid services such as frequency control, voltage control, and ‘synthetic mass inertia’.

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 and various installations for grid stabilisation and back-up power exist.

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

2.3.3.4 Potentials for large scale energy storage

Large battery systems are believed to represent an important part of the electricity supply system especially for electricity storage in the future for short to medium term storage (minutes to several hours) and capacities in the MWh range for grid stabilisation.

Yet, it has also been predicted that they will not become suitable for long term storage (days to months) and large capacities (tens of 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 (also e-hydrogen, PtH_2) and Power-to-Methane (also e-methane, $PtCH_4$). 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.

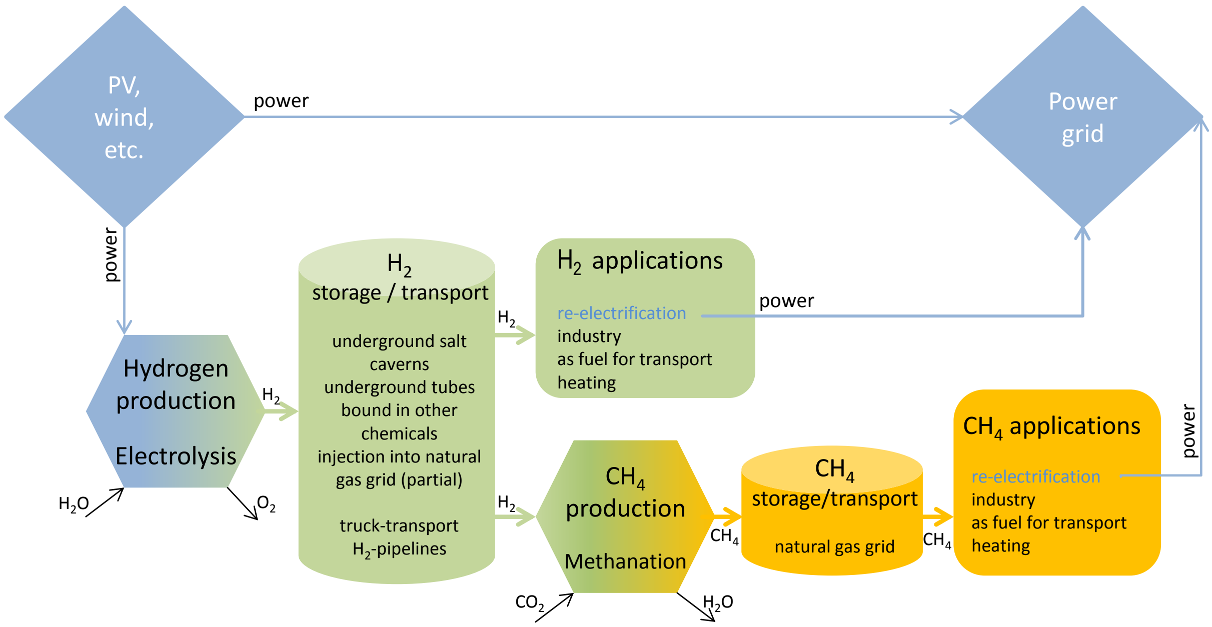


Figure 9: Basic concept of Power-to-Gas (Source: LBST)

Instead of storing it directly, hydrogen can 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 methane from hydrogen and carbon dioxide (CO_2). The resulting gas 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 synthetic methane. As synthetic methane 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 synthetic methane 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 synthetic methane 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. Synthetic methane 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 commercially available, but require further research and development before they can be applied in 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 synthetic methane from renewable electricity.

Figure 10: Power-to-Gas – demo projects in Germany 2013 (Source: LBST)

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, requires further research and demonstration activities.

2.3.4.4 Potentials for large scale energy storage

Power-to-Gas technologies (H_2 or synthetic methane) 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).

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.

Storage, distribution and power conversion technologies for natural gas and therefore for synthetic methane are state of the art and commercial unlike hydrogen technologies, as already mentioned in the chapter “Existing implementations” [Sterner 2009, p. 107]. Renewable methane from Power-to-Gas technologies can gradually replace conventional fossil natural gas using the same infrastructure. However, synthetic methane storage in the natural gas grid is related to challenges concerning the availability of ample cheap and easy accessible CO_2 sources particularly in the long term.

2.3.5 Power-to-Liquid

2.3.5.1 Principle, technical characteristics

The so called Power-to-Liquid (PtL) route includes the supply of liquid hydrocarbons. Gasoline, kerosene, and diesel can be produced via Fischer-Tropsch (FT) syntheses or via the methanol route.

In case of the methanol route methanol is synthesized using hydrogen and CO_2. Then the methanol is converted to gasoline, kerosene, and diesel via DME synthesis and dehydration (olefin production), oligomerisation and hydrogenation.

Methanol synthesis:	$3\ H_2 + CO_2 \rightarrow CH_3OH + H_2O$
DME synthesis:	$2\ CH_3OH \rightarrow CH_3\text{-}O\text{-}CH_3 + H_2O$
Olefin synthesis:	$CH_3\text{-}O\text{-}CH_3 \rightarrow (CH_2)_2 + 2\ H_2O$
Oligomerisation:	$0.5\ n\ (CH_2)_2 \rightarrow C_nH_{2n}$
Hydrotreating:	$C_nH_{2n} + H_2 \rightarrow C_nH_{2n+2}$

Per MJ of gasoline, kerosene, and diesel, a net amount of about 73.3 g of CO_2 is required. The CO_2 can be derived from biogas upgrading, from flue gas, from industrial processes (e.g. calcination of limestone), and from ambient air (no availability constraints). To generate a renewable transportation fuel, the CO_2 source also should be renewable. The energy requirement for CO_2 supply is low in case of CO_2 from biogas upgrading and very high in case of CO_2 from ambient air.

Figure 11 shows the main processes for the production of gasoline, kerosene, and diesel from renewable electricity (Power-to-Liquid) via the methanol route.

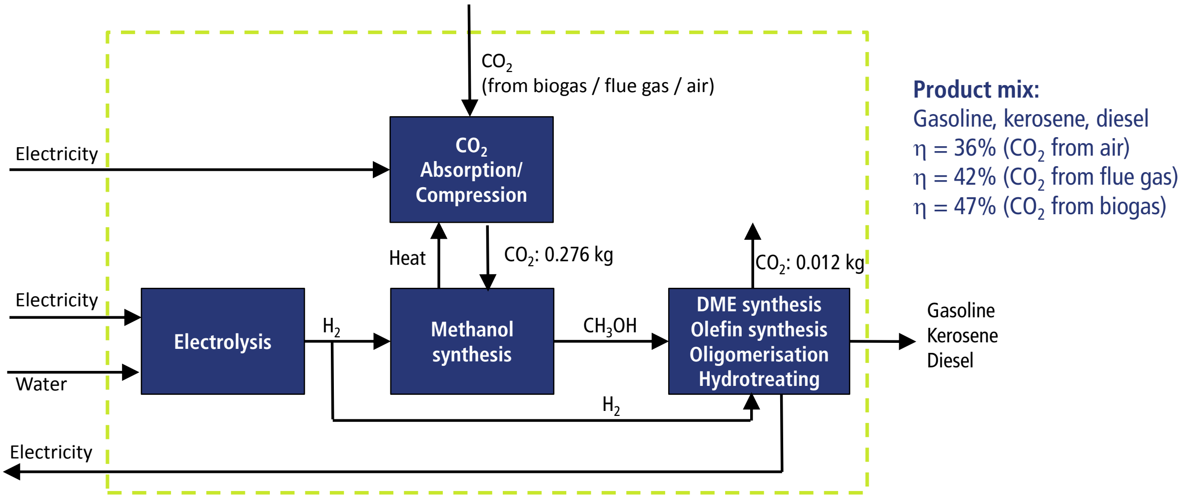


Figure 11: **Simplified flow chart for the production of gasoline, kerosene, and diesel from renewable electricity (Power-to-Liquid) via the methanol route (Source: LBST)**

In case of Fischer-Tropsch synthesis liquid hydrocarbons are synthesized using hydrogen and CO (Fischer-Tropsch synthesis with CO_2 does not work).

Fischer-Tropsch reaction: $(2n+1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$

Today, Fischer-Tropsch synthesis is carried out with a mixture of hydrogen and CO derived from coal gasification. In case of electrolytic hydrogen there is no CO and the CO has to be derived from CO_2. CO can be generated from CO_2 via the reverse CO shift reaction.

Reverse CO shift: $CO_2 + H_2 \rightarrow CO + H_2O$

In real plants the production of liquid hydrocarbons from H_2 and CO consists of Fischer-Tropsch synthesis and downstream upgrading. In case of the Shell Middle Distillate Synthesis (SMDS) process the Fischer-Tropsch-Synthesis step generates long-chain hydrocarbons which are processed further via hydrocracking to achieve a maximum yield of naphtha, kerosene and diesel and minimum amounts of gases (mainly propane and butane).

Figure 12 shows the main processes for the production of naphtha, kerosene, and diesel via the Fischer-Tropsch synthesis route.

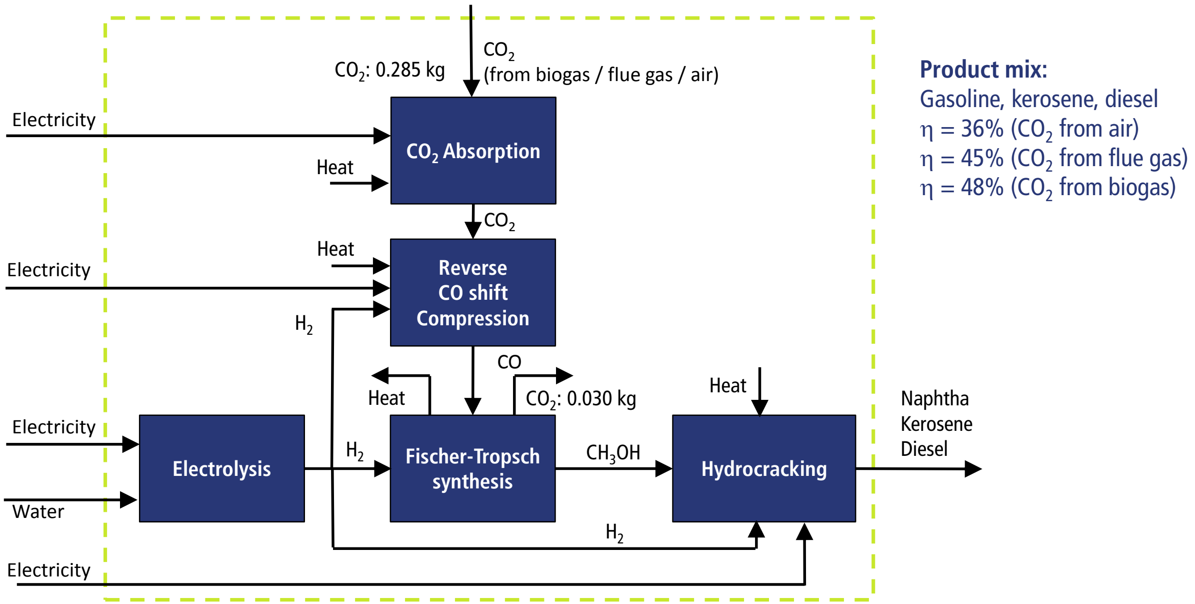


Figure 12: Simplified flow chart for the production of gasoline, kerosene, and diesel from renewable electricity (Power-to-Liquid) via the Fischer-Tropsch synthesis route (Source: LBST)

Table 5 shows the product split of the final products from the SMDS process.

Table 5: Product split of the products from the SMDS process (%-mass) (Source: [Senden et al 1996])

	Gas oil mode	Kerosene mode
Naphtha	15	25
Kerosene	25	50
Gas oil (diesel)	60	25

In contrast to the methanol route, the octane number of the naphtha fraction is too low for Otto engines being provided by the Fischer-Tropsch route. As a consequence, if the naphtha fraction should be used in Otto engines, the naphtha fraction has to be processed further (e.g. via isomerisation) to elevate the octane number.

Both methanol and the Fischer-Tropsch synthesis reaction are exothermal. In combination with high temperature electrolysis, the heat released (T = 220 to 250°C for low temperature Fischer-Tropsch synthesis) can be used to save electricity to generate steam as input to the electrolysis (and CO_2 splitting) as the electricity requirement for the electrolysis of steam is lower than that for liquid water.

Based on this concept the German company Sunfire states to achieve an electricity-to-hydrocarbon efficiency of up to 70% (LHV; without CO_2 supply) [Sunfire 2013]. In comparison, the electricity-to-hydrocarbon efficiency for the production of liquid hydrocarbons in combination with alkaline and PEM electrolysis amounts to about 50% (LHV; without CO_2 supply).

High temperature electrolysis is based on the solid oxide electrolysis cell (SOEC) technology which is still in the R&D stage. Until now no long term experience (> 40,000 h) is reported. Also, there is no concept how to integrate SOEC in highly fluctuating renewable energy based systems.

2.3.5.2 System integration

PtL technology provides the potential for bulk power and long term energy storage (days, weeks, months) in conventional liquid fuel tanks like today's liquid fossil fuels from crude oil.

Beside applications in the transport sector, synthetic diesel can be used for stationary applications, e.g. in peak power plants deploying diesel engines and gas turbines from several kW to several hundred MW range.

An open issue is the operation of the synthesis process in combination with fluctuating renewable energy sources such as wind power and photovoltaic electricity. Buffer storage of hydrogen can partly decouple hydrogen production from downstream processes via electrolysis (not possible in case of high temperature electrolysis used in the Sunfire process) facilitating the operation with fluctuating electricity supply. E.g., the intermediate products (e.g. methanol) can easily be stored and as a result methanol synthesis can be decoupled from downstream processes which also facilitate the operation in combination with fluctuating electricity supply.

2.3.5.3 Existing implementations

In Grindavík in Island a plant for the generation of methanol from hydrogen and CO_2 has been in operation since 2009 (George Olah CO_2 to renewable methanol plant). CO_2 is derived from the Svartsengi geothermal power station and hydrogen is generated via electrolysis using renewable electricity. The plant is owned by Carbon Recycling International (CRI) and is jointly operated by HS Orka and CRI [ChemTech 2013]. The plant converts 4,500 t of CO_2 to about 18,000 m^3 of methanol per year.

Another pilot plant for the production of methanol from renewable electricity has been built by Swiss Silicon Fire AG and is located in Altenrhein, Canton St. Gallen in Switzerland [Meyer-Pittroff 2013].

The process for the conversion of methanol to gasoline, kerosene, and diesel is commercially available. Lurgi calls its proprietary process 'MtSynfuels'. The share of gasoline, kerosene, and diesel depend on the operation mode. At maximum middle distillate mode 89% of the liquid hydrocarbons consist of kerosene and diesel (LHV) [Lurgi 2004]. At 'kerosene mode' the share of kerosene of the liquid hydrocarbon fraction amounts to about 49% by mass which is approximately 49% (LHV) [Lurgi 2005]. The gasoline fraction has an octane number of 92 (RON) which is sufficient for the operation in most road vehicles with Otto engines. Elevation to RON 95 is possible via further processing with conventional refinery processes in order to reach a RON of 95 which is the RON of the ‘standard gasoline’ in the EU.

2.3.5.4 Potentials for large scale energy storage

PtL offers the advantage of storaging large amounts of energy in liquid state. The disadvantage is the low efficiency of only about 15 to 29% (full cycle using H_2 production via alkaline and PEM electrolysis) depending on the efficiency of the re-electrification and the CO_2 source (biogas upgrading, ambient air).

Storage, distribution and power conversion technologies for gasoline, kerosene, and diesel have been state of the art since decades.

Gasoline and diesel produced via PtL can be used in existing road vehicles, diesel fuelled trains and ships.

Furthermore, kerosene via PtL can be used as renewable aviation fuel. At maximum kerosene level about 50% of all liquid hydrocarbons are kerosene [LBST 2014].

The market readiness of the technology is notably depending on the interest of potential industry partners and financial investors. Gasoline and diesel for road vehicles could be produced at industry scale in 2020 the earliest. First tank fills for planes are expected to be provided already at the end of 2016 [Sunfire PtL 2014].

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 6 provides a comparison of different large scale energy storage technologies including stationary batteries. All battery technologies are showing a comparatively small storage capacity (kWh - MWh range). Therefore, the main application for battery technologies is in mobile and isolated network applications. Because of the existence of more appropriate solutions (e.g. cheaper technologies, larger storage capacities), their application for long term storage on a European scale is not expected.

The technical parameters in Table 6 are the following:

- Power rating: range of the discharge power for which the respective storage technology can be applied (for the PtG / PtL cases both the charging and discharging power rating is given);
- Installed capacity in Europe: where applicable the installed power capacity is summed up;

- Energy rating (charging): time required to charge the storage system from empty stage to full charge at full power;
- Response time: time from activation of storage system to the provision of the full power installed;
- Lifetime: period in which the system can be used for electrical energy storage;
- Round-trip efficiency: efficiency from electricity via storage back to electricity at a later point in time;
- Investment per power installed: today's (2013) investment costs in € for installing 1 kW of the respective storage technology;
- Investment per capacity installed: today's (2013) investment costs in € for installing 1 kWh of the respective storage technology.

The comparison of literature concerning Power-to-Gas systems shows a wide range: power rating is in the range of 1 kW to several GW, the storage capacity is in the range of hours to several weeks. To provide a meaningful comparison, the four following relevant Power-to-Gas system cases have been compared and therefore for these cases 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, synthetic methane underground storage in salt caverns, later gas 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 0.3 $MW_{el.in}$ 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 cases investigated the only feasible option for large scale energy storage is to employ underground hydrogen / synthetic methane storage in salt caverns. Synthetic methane 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 6: Comparison of large scale storage technologies (technical storage performance)
(Source: LBST based on [IfEU 2009], [JRC 2011], [Garche 1999], [Gildemeister 2013a], [Gildemeister 2013b], [NGK 2013], [Store2.1 2012], [Wärtsilä 2013], [Younicos 2014], [Genoese 2013])

Storage technology → / ↓ Performance criteria		PHES	CAES	ACAES	Power-to-Gas systems (with re-electrification)					PTL	Large scale battery storage (Data are based on published literature. Permanent improvements are ongoing.)			
					E-H_2 - cavern - CCGT(reference) LBST case example	E-H_2 - syn. methane prod. - cavern - CCGT LBST case example	Large scale H_2 technologies literature bandwidths	E-H_2 - underground tubes - FC LBST case example	E-H_2 - vessel bundles - FC LBST case example	E-H_2 - H_2 buffer storage - Diesel prod. - CCGT or ICE-ST LBST case example	Lead Acid	Lithium Ion	Sodium Sulphur	Redox-Flow
Power rating	MW	10 - 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	~200MW el. in 290-360 MW el.out	0.001 - 50	0.001 - 50	0.5 - 50	0.01 - 10
Installed capacity Europe	MW	45,600	321	-	-	-	-	-	-	-	20 - 30	~20	1	~1
Energy rating (charging)	Charge time	1 - 24 h +	1 - 24 h	1 - 24 h	54.5 days	44.5 days	s - 24 h+++	1.5 days	1.5 days	60 days	s - h	s - h	s - 6 h	s - 10 h
Response time		10 sec - 2min	15 min cold start	5 - 15 min	min	min	min	min	min	min	ms	ms	ms	ms
Lifetime	years	50+++	30 - 40[3]	30 - 40[3]	20	20	5 - 20	20	20	>20	3 - 15	5 - 20[4]	15	5 - 20
Round-trip efficiency	%	70 - 85	42 - 54	~70	35	24	20 - 50	28	31	18 - 22[5]	60 - 95	95 (DC)[4] ~85%(AC)	85 - 90 (DC) 75% (AC)	70 - 80 (DC)
Investment per power installed[6]	€/kW	470 - 2,200	450 -1,150	600 - 1,200	1,274 el. out	1,824 el. out	1,050 - 3,000	4,198 el. out	4,861 el. out	2,300 - 2,600 el. out	200 - 650	700 - 3,000	700 - 2,000	4,000 - 9,000[7]
Investment per capacity installed[6]	€/kWh	8 - 60	10 - 90	10 - 120	8	11	1 - 50	117	135	9 - 11	100 - 300	200 - 1,800	200 - 900	1,000 - 2,000[7]

[3] Not specified if related to above or below-ground technology
[4] Samsung SDI 200 kW, 200 kWh: 95% DC, 4,000 cycles, 20 years
[5] CO_2 from ambient air; efficiency electrolysis: 65% [JEC 2013]; lower limit: based on power plant Quisqueya I & II, Dominican Republic, consisting of dual fuel engine Wärtsiläe 18V50DF with downstream steam turbine (ICE-ST), efficiency: 48% [Wärtsilä 2013]; upper limit: diesel fuelled CCGT, efficiency: 60%
[6] Today's costs; application cost can vary; for ACAES: costs are converted from US$ with conversion rate 1 US$ / 0.8 €
[7] Gildemeister: CellCube FB 200-400 (200 kW, 400 kWh): ~0.8 Mio. €; CellCube FB 200-1600 (200 kW, 1600 kWh): 1.8 Mio. €

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 / Power-to-Liquid 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 13). In Figure 14 a comparison of the volumetric storage densities of these technologies is depicted.

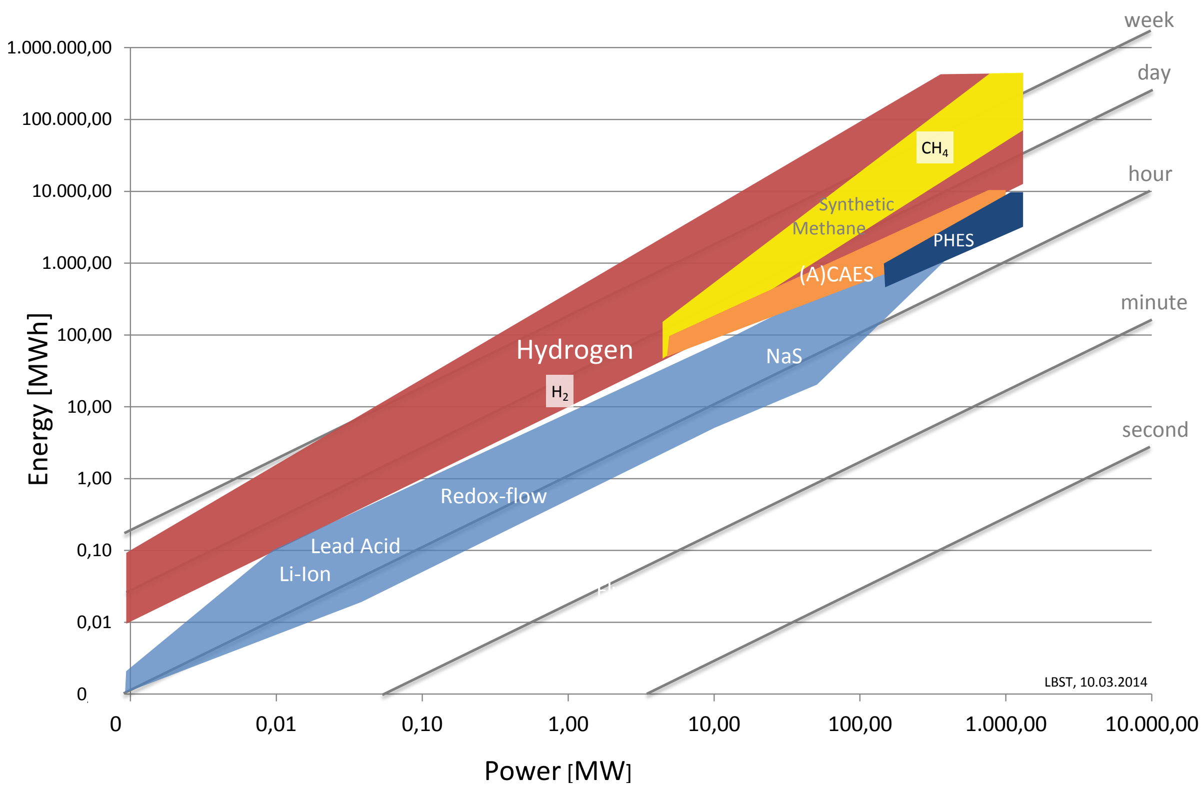


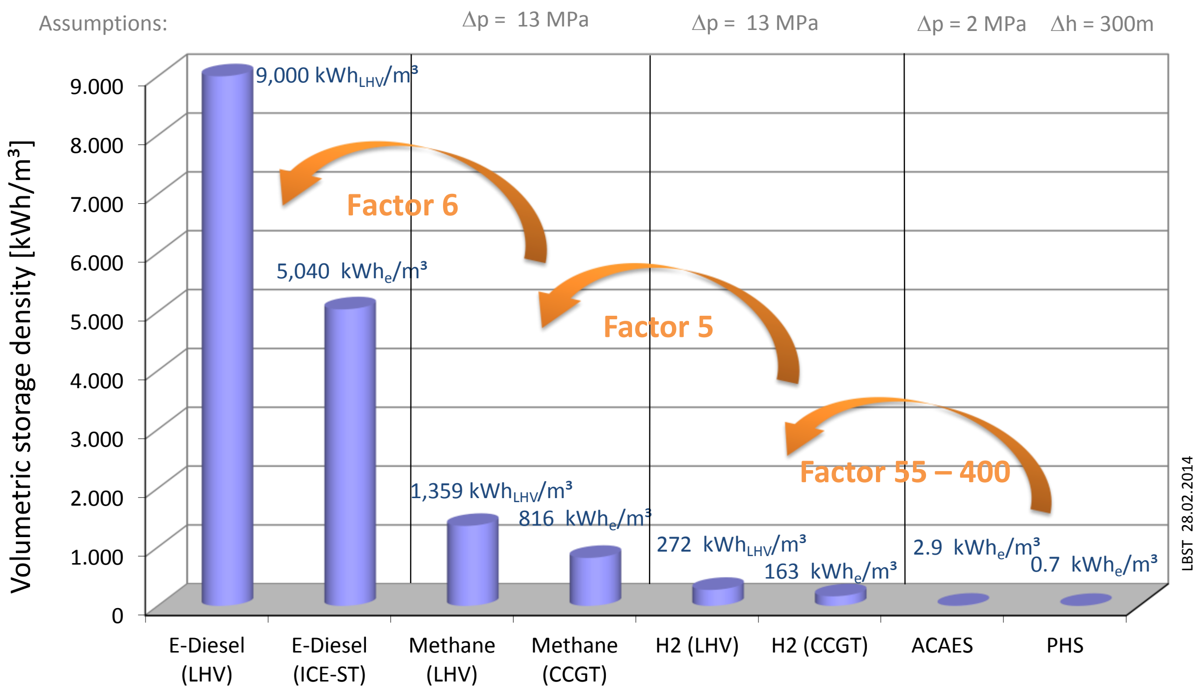
Figure 13: Assessment of technical storage performance (Source: LBST)

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 methane 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.



*Note: assumption: efficiency CCGT: 60%; efficiency ICE-ST: 52%.

Figure 14: Gravimetric and volumetric storage densities, chain efficiency (Source: LBST)

2.4.2 Assessment of storage economics

Generally, the cost of a power plant can by divided into capital (invest) cost for the construction and variable cost for the operation of the power plant. The costs of electricity storage depend on several factors – see Figure 15.

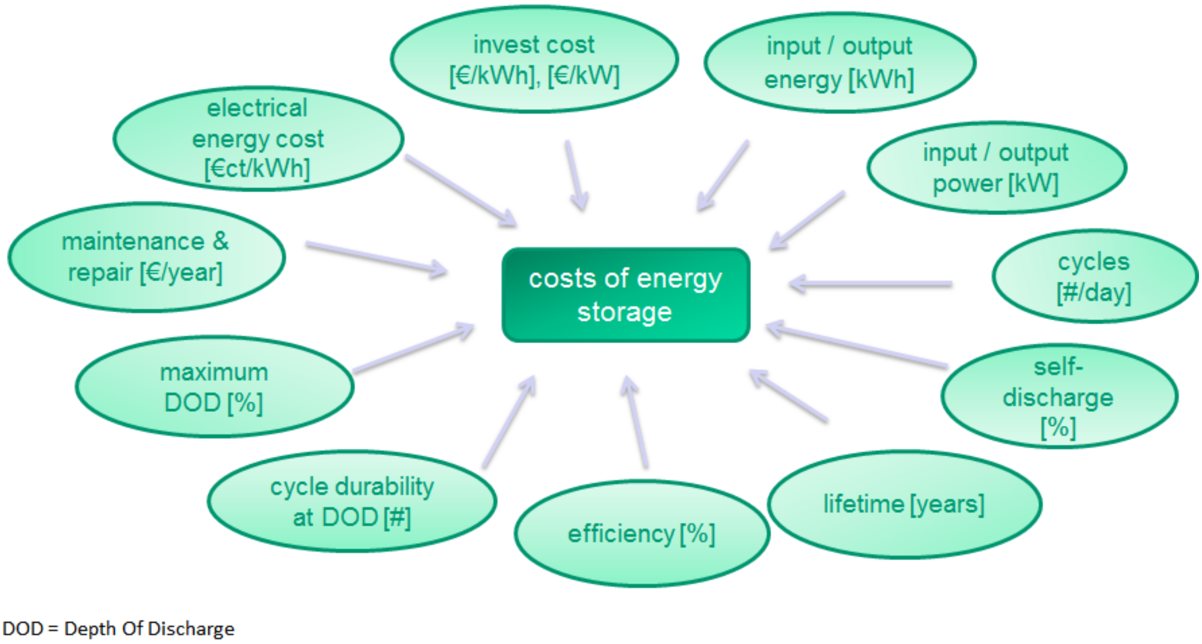


Figure 15: Influential parameters on the costs of energy storage (Source: LBST)

The storage of electrical energy is always related to significant costs. Large scale storage such as PHES, (A)CAES, Power-to-Gas (H_2 and synthetic methane) and Power-to-Liquid requires a large investment with regard to the power installed, but they are comparatively cheap with regard to the capacity installed. The investment costs are described in the following sections.

The bandwidth of information regarding investment costs of large scale electricity storage systems is very large (see Table 6) and in Figure 16 data are summarized graphically in order to provide the ballpark. The graph depicts both the bandwidths for the power specific and the energy specific investments independent from each other. There is no direct coupling between the electric power installed and the electric energy (capacity) to be stored.

The investment costs for existing pumped hydro storage systems are in the range of 550 - 1,150 €/kW. This large bandwidth is caused by a strong dependency of the investment costs on the conditions of a specific site [Deane 2010]. According to [Store 2012] the investment costs per kW for PHES plants planned in Europe until 2020 are between 470 €/kW and 2,170 €/kW.

Both existing CAES power plants needed about the same specific investment costs of ~ 400 €/kW [Store2.1 2012]. Current investment costs are estimated to be between 450 and 1,150 €/kW. The investment costs for adiabatic CAES power plants are higher, as they require a heat storage system in addition and a more costly high temperature compressor.

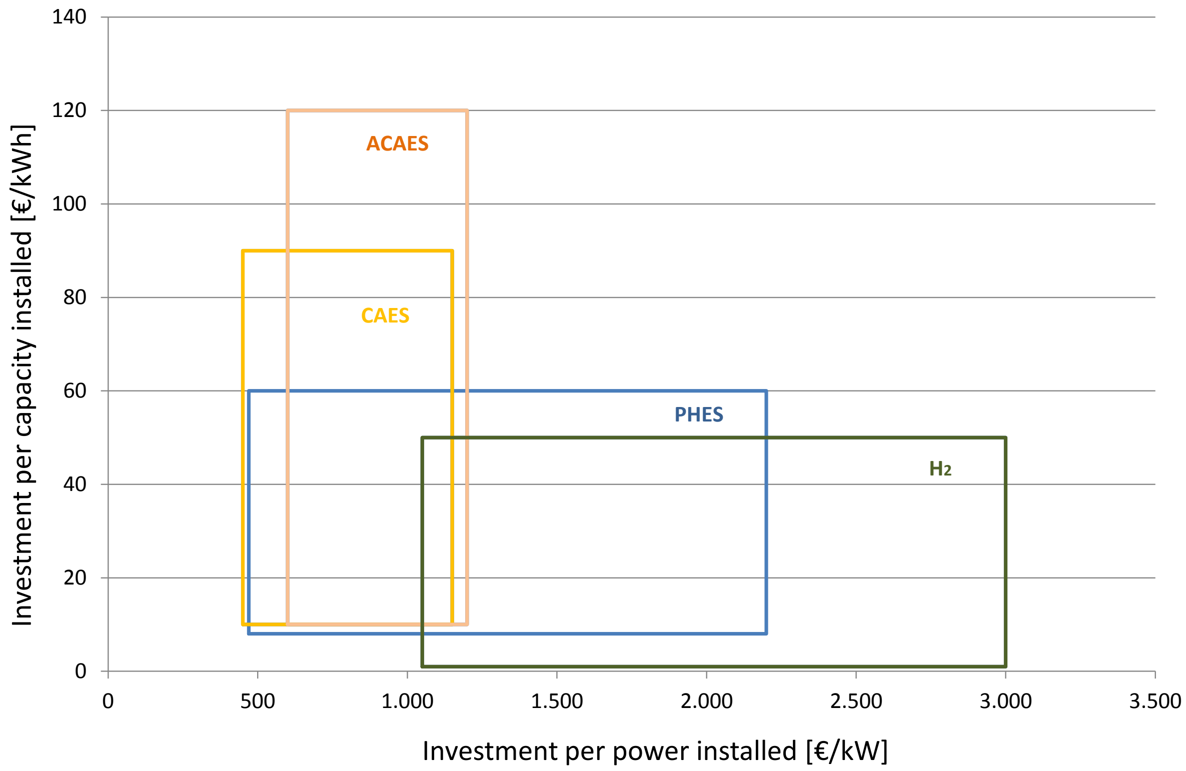


Figure 16: Overview of the relative investments of the electricity storage technologies (Source: LBST based on [Genoese 2013], [Store 2012])

The bandwidth of investment costs for the PtG technology is even larger (1,050 - 3,000 €/kW). This reflects mainly the unknown near and medium term future of this technology. Technical improvements in hydrogen electrolysis may enable a significant reduction of investment costs [Genoese 2013]. The energy specific investment is given to be up to 50 €/kWh (partly only in the range of 1-15 €/kWh).

Due to the relatively high volumetric energy density of hydrogen the amount of energy to be stored in a given salt cavern is much higher than e.g. than that of compressed air.

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.

The results of the German Case Study show that the overall hydrogen costs range from 4-6 €/kg$_{H_2}$ and the costs structure is rather similar for all hydrogen applications.

Major cost drivers are represented on the one hand by the investment costs for the electrolysis and topside equipment (CAPEX) and on the other hand by the electricity costs for the hydrogen production (predominantly coming from the actual electrolysis operation in combination with small electricity consumption of the other topside equipment and the electrolysis stand-by operation). The impact of the cavern investment costs on the overall investment costs is rather small especially for large cavern plants.

As also stated in the HyUnder German Case Study Report the rationale for the observed results can be derived from the analysis of the specific cost structure and allowable prices as presented in Figure 17 below. For the sectors mobility, industry and NG grid injection the specific hydrogen costs (overall costs including annualized capital expenditures divided by the overall hydrogen amount sold to the market) are between 4.50 and 5.00 €/kg$_{H_2}$. The substantially higher costs for hydrogen sold to the electricity markets of more than 6.00 €/kg$_{H_2}$ are due to additional investment costs for the CCGT power plant and additional efficiency losses of the re-electrification process (and thus higher hydrogen consumption and electricity purchases from electrolysis for a comparable hydrogen demand). The cost structure is similar for all sectors and markets: major cost components are annualized investment costs (with major share of electrolysis investments and minor share of cavern investments) as well as electricity costs for operating the electrolysers, minor cost components are fixed operating costs (i.e. O&M costs as a fixed percentage of the investment costs), all other costs being negligible. The average price assumptions paid to purchase electricity from the market range between ca. 39-46 €/MWh$_{el}$ in 2025 and between ca. 35-47 €/MWh$_{el}$ in 2050.

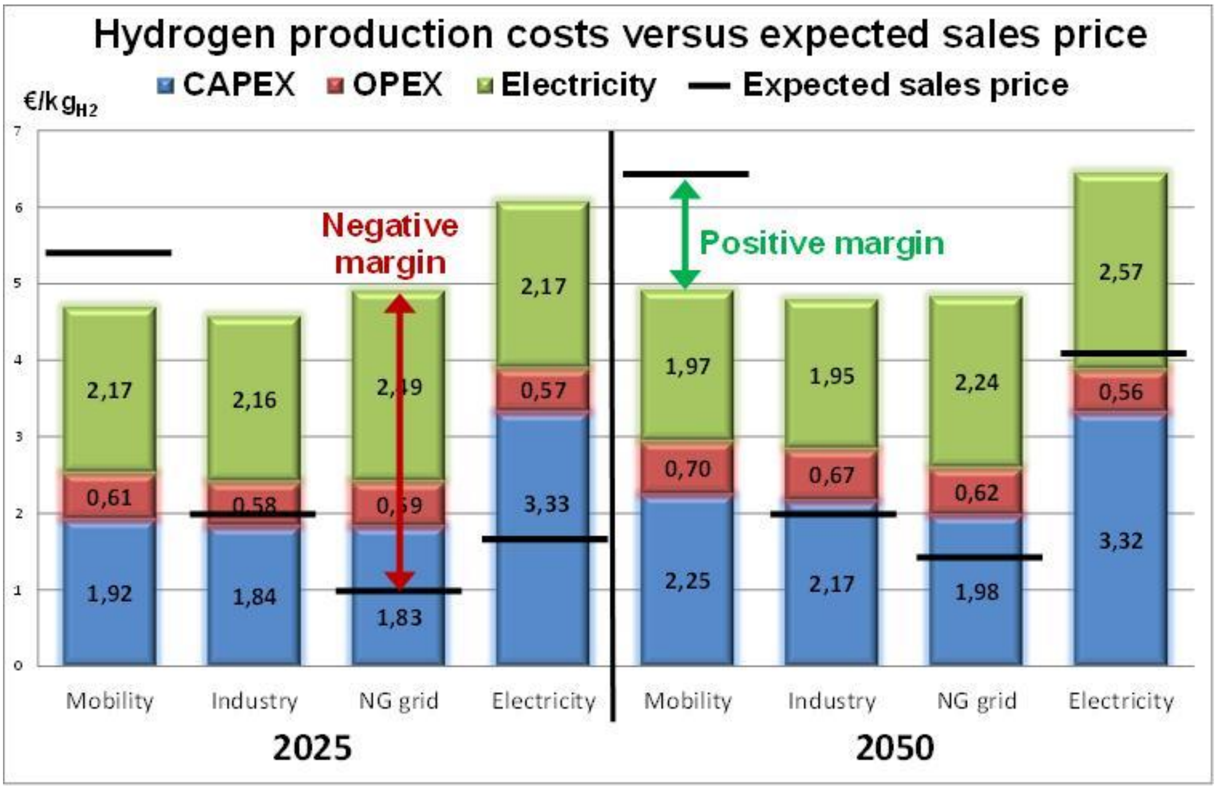


Figure 17: Achievable prices for hydrogen in €/kg$_{H2}$ (Source: HyUnder WP6, German Case Study)

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 safety (and safety perception), 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.

It is important to mention that the chapter 3.2 “Safety of underground storages” is only focused on the public perception of safety, summarizing in high level safety constraints related to underground gas storages. The technical components and concepts are explained in detail in Deliverable 3.4 “Detailed study of the key candidates for underground hydrogen storage and scoring for the various options” of the HyUnder project.

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, and
- 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 “Overview on all known underground storage technologies” of the HyUnder project.

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 “European Energy Framework” of the present report. The European Commission program “Energy 2020 - A strategy for competitive, sustainable and secure energy” and the “Energy Roadmap 2050”, both 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 has 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 *Safety of underground storages*

3.2.1 Introduction

Salt caverns, gas reservoirs in depleted oil or gas reservoirs and aquifer formations provide excellent conditions for the safe storage of large volumes of natural gas and with some restrictions of hydrogen in future. The main attributes of these types of storages are as follows:

- The high degree of tightness (impermeability) of the sealing rock layers above the reservoirs or the rock salt surrounding the salt caverns
- The thickness of the sealing geological formations measuring several tens or hundreds of metres compared to the wall thicknesses of surface tanks of only a few centimetres
- The large distance to the surface of several hundred metres
- The huge storage capacities so that far less individual storages are required compared to surface tanks, and therefore the much lower risk of a technical failure. Typical underground storage plants can have the capacity to store the same volume of gas that could easily fill over 1,000 spherical surface gas tanks.

The total amount of gas stored in underground storages worldwide today is almost 400 billion m³ natural gas (working gas). This corresponds to over 10% of the annual natural gas production, a huge amount of energy. This should also be seen in the light of the relatively small number of incidents or accidents which have occurred in this sector in the last approx. 40 years since underground storages have been operated at an industrial scale.

Moreover, the already very small number of incidents has decreased even further in recent years, even though the storage capacities have undergone considerable growth in the last ten years in particular. 40 years of experience, coupled with very stringent safety regulations – in Europe in particular – have given rise to very high levels of operational safety.

3.2.2 Incidents and accidents in natural gas storages in deep underground formations

The following descriptions are primarily based on unpublished documentation from W.E.G. (Association of the German oil and gas production industry) and the comprehensive work of D.J.Evans for the British Geological Survey (BGS): “An appraisal of underground gas storage technologies and incidents, for the development of risk assessment methodology” [EVANS 2009].

The known incidents and accidents can be divided into the following categories: Problems

- when drilling the access well(s),
- in the access well,
- around the wellhead,
- underground,
- during work-overs,
- when operating outside the permissible storage pressures, and
- involving the tightness (integrity) of the cover rock in aquifer storages.

It is interesting to note here that the categories, and therefore the incidents, primarily involve the access well(s). The consequences of difficulties affecting this part of the system are all localised, and do therefore not put into question the integrity of the whole storage system.

3.2.3 High safety standards in Europe

Stringent regulations are in place in Europe regarding the planning, layout, construction and subsequent operation of underground gas storages. The benchmarks for this legislation were originally established by the authorities and industries in the individual countries – with France and Germany in particularly paving the way for the development of underground gas storages. During this process, the specifications laid down by the competent authorities and the companies themselves, were continuously adjusted to incorporate the latest findings and experience.

The high safety standards in Europe will be explained using the layout of gas cavern production wells as an example. Unlike the situation in the USA, where the stored gas is produced directly via the innermost cemented casing, European regulations stipulate the mandatory use of a special production string. This is done to allow the integration of a permanent and accurate leakage detection system in the well. In addition, subsurface safety valves have also been mandatory in Europe for many years now. These can automatically seal off the storage underground in the event of accidental or deliberate damage to the cavern wellhead.

3.2.4 Conclusions

Gas storage in deep underground formations forms the basis for particularly safe operations. The number of known incidents and accidents is very small compared to the large number of facilities in operation, and the enormous volume of gas stored in each cavern field. The known cases are primarily associated with the shortage of experience available in the early days of developing this underground storage technology, as well as a consequence of human error. Today a very high level of safety has been attained, especially in the light of the very stringent safety regulations stipulated in Europe, and the lessons that have been learned.

3.3 *Energy storage associations*

This chapter presents an overview 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. Furthermore, in 2014 the Global Energy Storage Alliance (GESA) has been established. GESA is a non-profit organization and its mission is to advance education, collaboration, knowledge and proven frameworks about the benefits of energy storage and how it can be used to achieve a cleaner, more efficient, reliable, affordable and secure electric power system globally. GESA was jointly founded by the California Energy Storage Alliance (CESA), the Germany Energy Storage Association (BVES), the China Energy Storage Alliance (CNESA), the India Energy Storage Alliance (IESA), the USA-based Energy Storage Association (ESA) and the Alliance for Rural Electrification (ARE).

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 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.

3.4 *Past and on-going projects*

Past and on-going projects on energy storage are 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.

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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 18, 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.

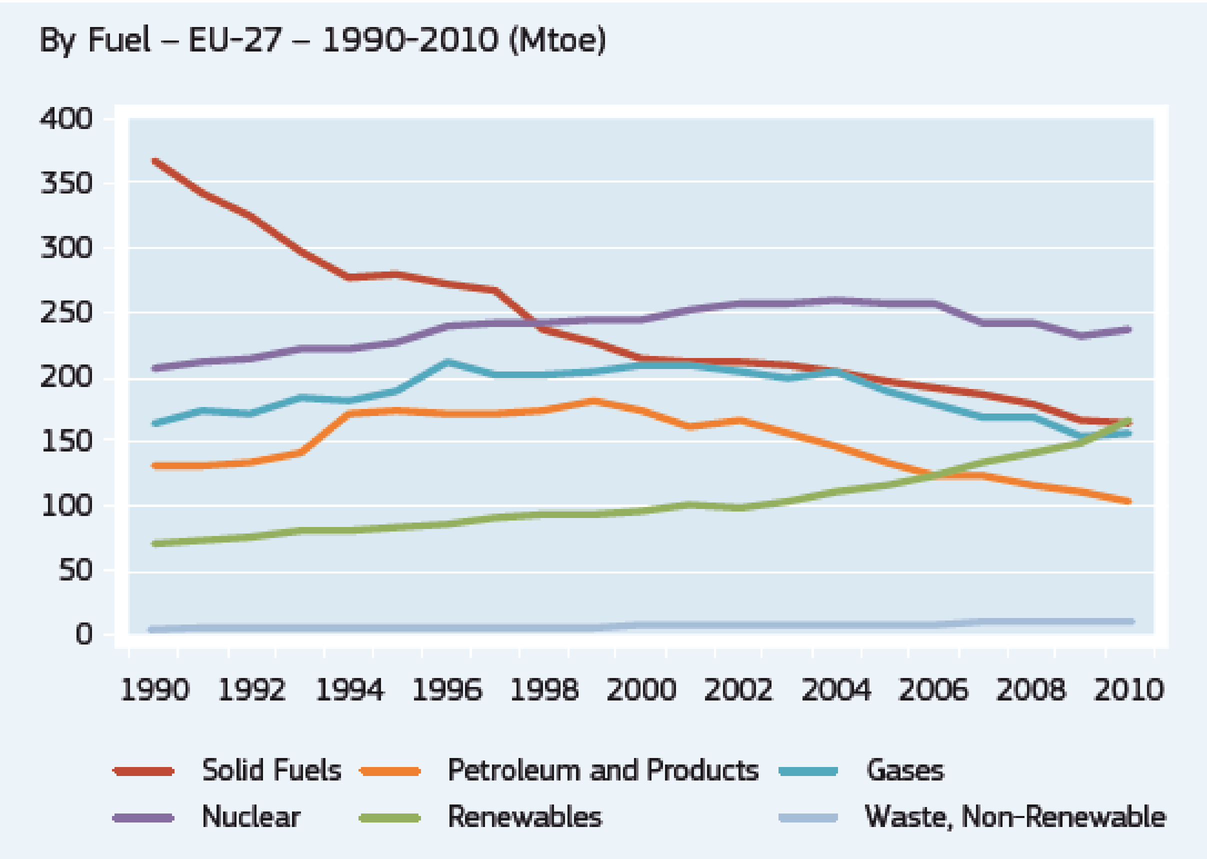


Figure 18: European energy generation by fuel, 1990 – 2010 (Mtoe) (Source: [EUEF 2012])

Since 1990 to 2010 the gross inland energy consumption has remained stable, as it is depicted in Figure 19.

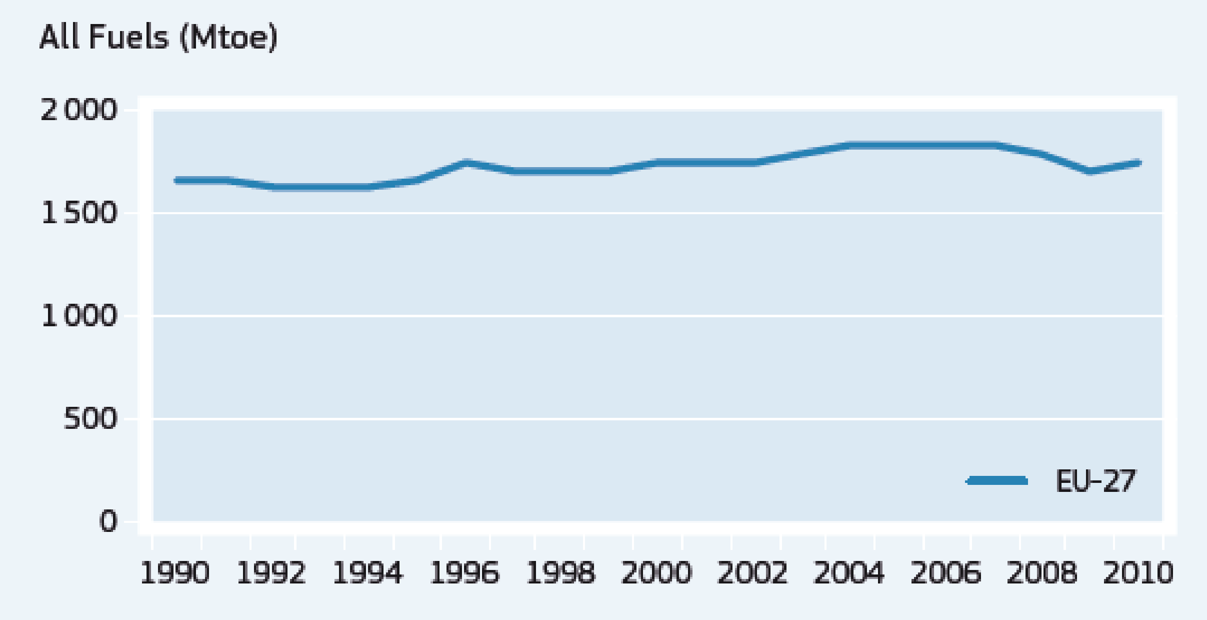


Figure 19: Gross inland energy consumption, 1990 – 2012 (Source: [EUEF 2012])

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 20, 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).

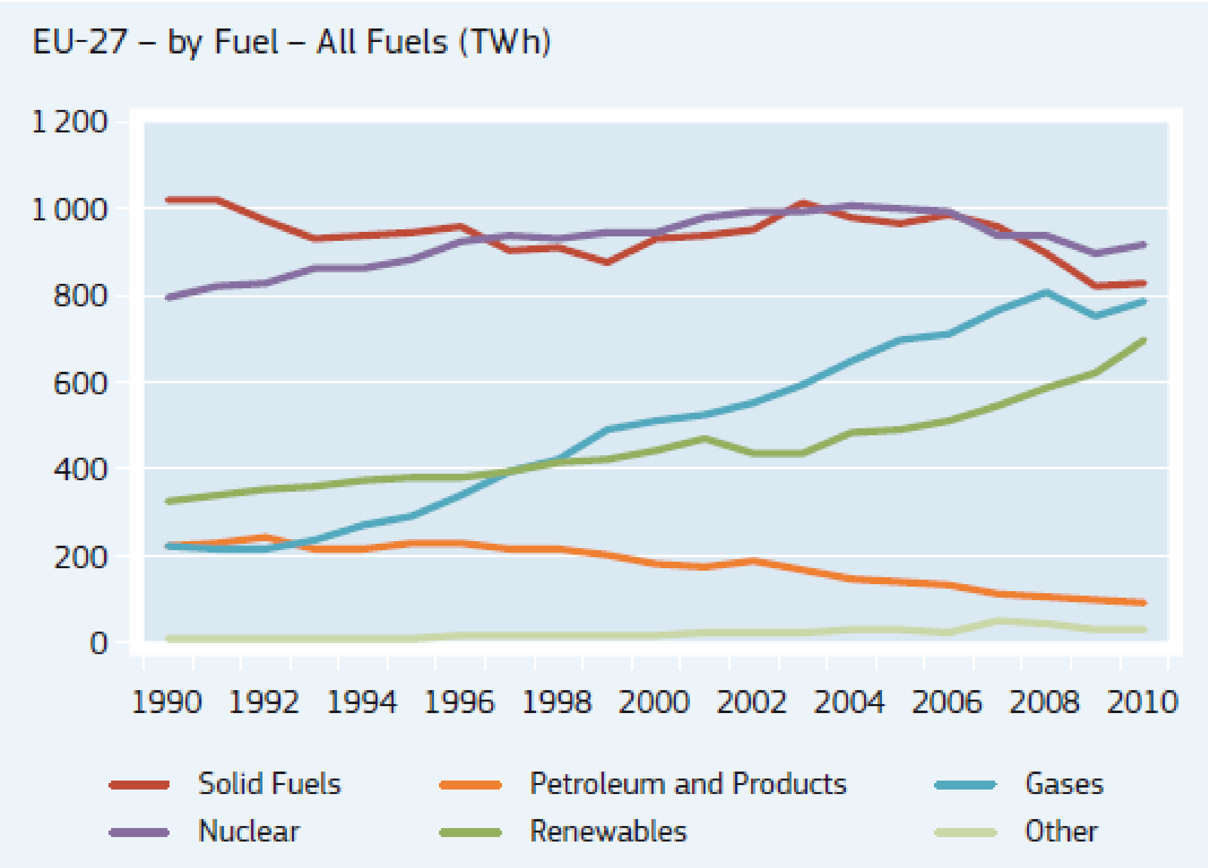


Figure 20: **Gross electricity generation in the EU by fuel, 1990 - 2010 (TWh) (Source: [EUEF 2012])**

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 21.

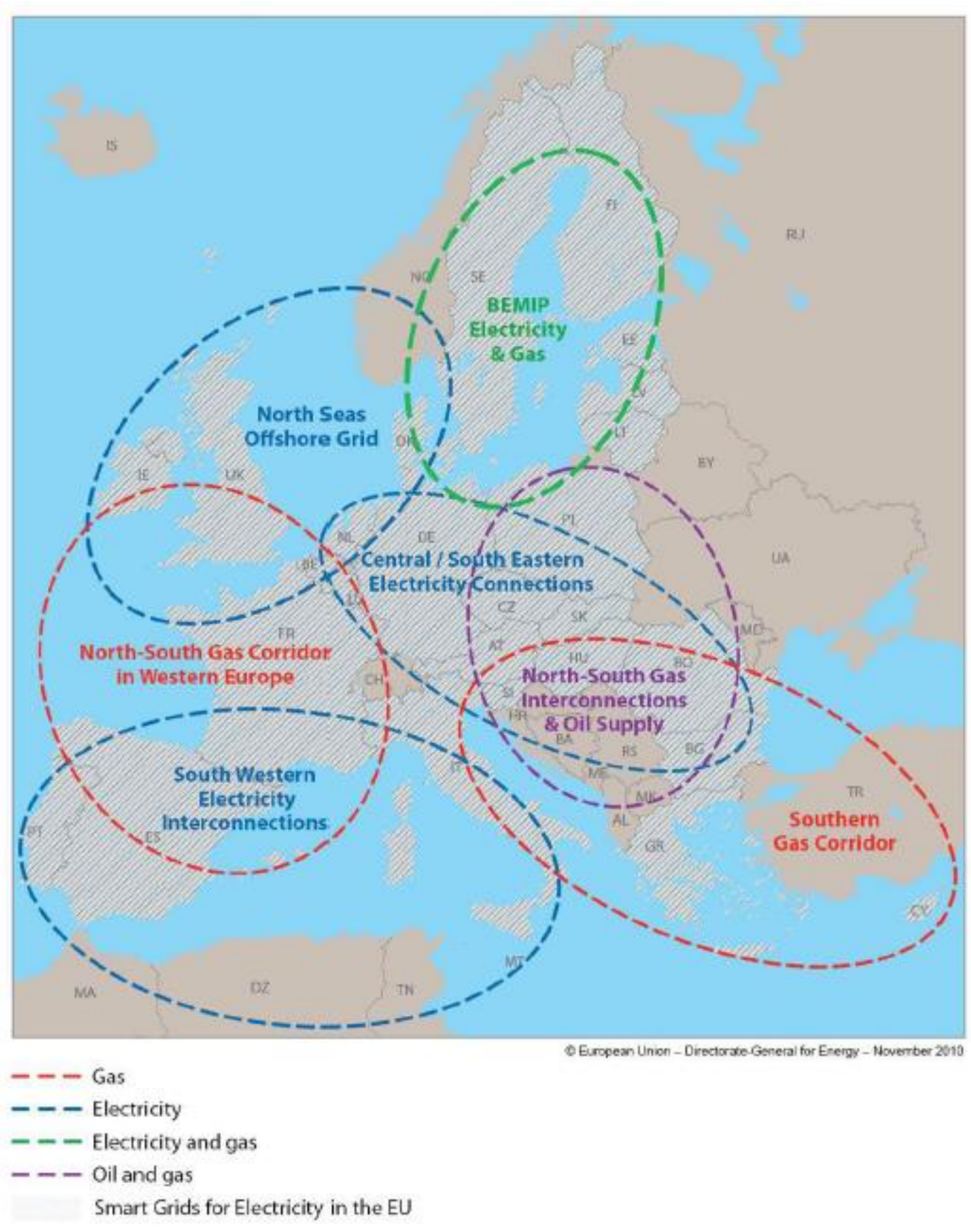
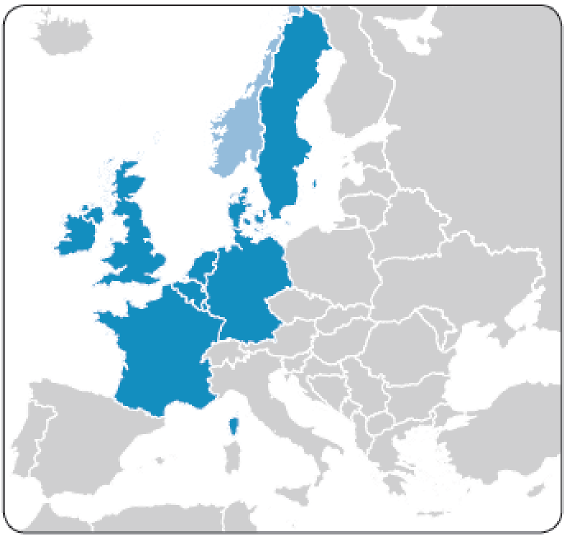


Figure 21: Priority corridors for electricity, gas and oil (Source: [EIP 2010])

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 (see natural gas supply crisis 2009) and will motivate ambitious international projects based on Power-to-Gas technologies and hydrogen underground storage.

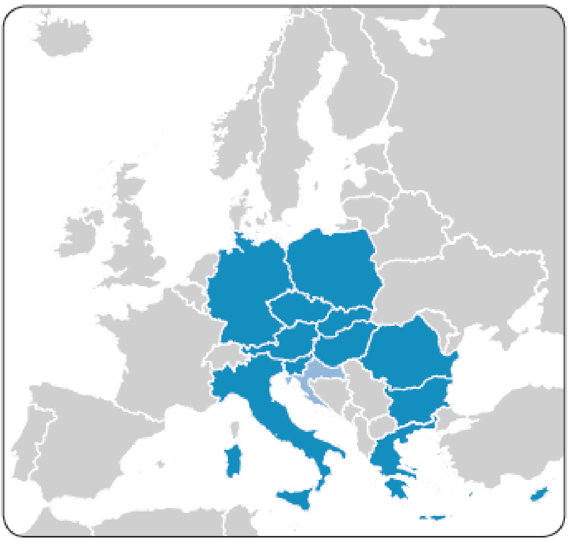
In the following paragraphs, the different HyUnder cases are presented country by country: Germany, France, United Kingdom, The Netherlands, Romania and Spain.

The German case study must take into account the North Sea offshore grid (see Figure 22). 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 23, by the North – South gas corridors, see Figure 24 and Figure 25, and by the BEMIP (Baltic Energy Market Interconnection Plan) to some lesser extent (Figure 23). 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.



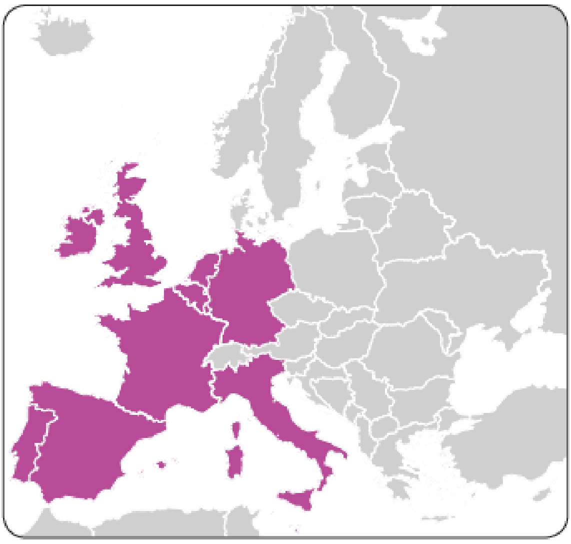
Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between Denmark and the Netherlands
New sub-sea interconnector between France and the UK
New sub-sea interconnector between the UK and Belgium
Sub-sea interconnector and hub between Germany/ UK and Norway[6]
AC land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

Figure 22: North Sea offshore grid (Source: [EIT 2011])



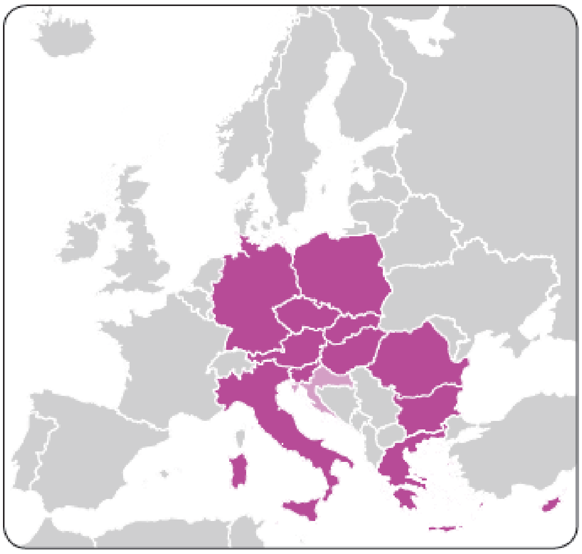
Projects to be considered as potential PCIs (list is not exhaustive)
New interconnection between Hungary and Slovakia
New interconnection between Germany and the Czech Republic
New interconnection between Slovenia and Italy
Interconnection upgrade between Bulgaria and Romania, and Bulgaria and Greece
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 23: 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

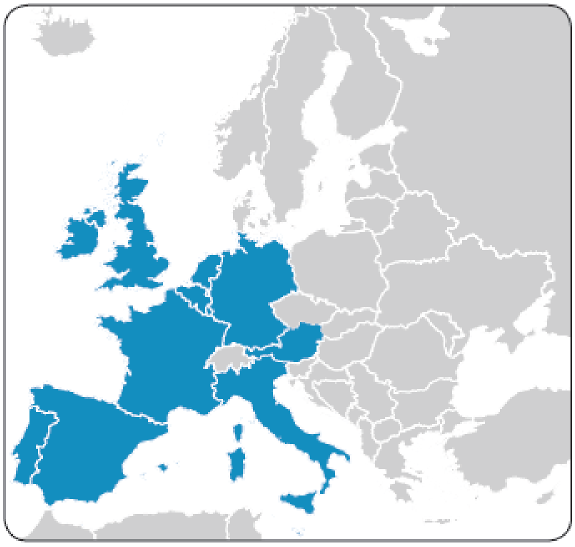
Figure 24: North-South gas interconnections in Western Europe (Source: [EIT 2011])



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 25: 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 22, the North-South gas interconnections in Western Europe, see Figure 24, and the South Western electricity interconnections, see Figure 26. 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 26: 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 22, and by the North – South gas corridors, see Figure 24 and Figure 25.

The Spanish case study will be affected by the South Western electricity interconnections, see Figure 26, and by the North-South gas interconnections in Western Europe, see Figure 24. The UK case study will be affected by the North Sea offshore grid, see Figure 22, and by the North-South gas interconnections in Western Europe, see Figure 24.

The Romanian case study is affected by the North-South gas interconnections in Central Eastern and South Eastern Europe, see Figure 25, by the North – South electricity interconnections in Central Eastern and South Eastern Europe, see Figure 23, and by the Southern Gas Corridor, see Figure 27. The Southern Gas Corridor will increase security of supply in the region and will allow Power-to-Gas initiatives.

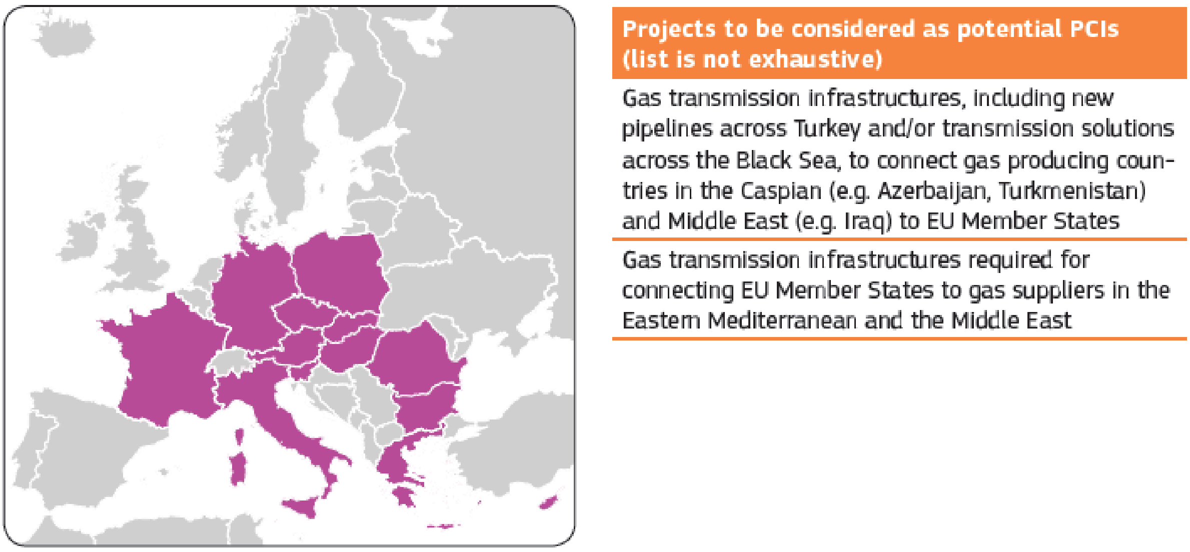


Figure 27: Southern Gas Corridor (Source: [EIT 2011])

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 7: Overview of scenarios for the Energy Roadmap 2050 (Source: [ER2050 2011, p. 4])

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 Diversifiedsupply technologies scenario but assuming that CCSis delayed, leading to highershares for nuclear energy with decarbonisation driven bycarbon 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 (ar ound 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 enable seasonal management of supply demand and to avoid supply constraints due to geopolitical instabilities in the exporting countries. Natural gas working volumes and storage capacities are listed in Table 8.

Table 8: Natural gas volume and storage capacity EU-27 (Source: [FRCES 2013, p. 4])

	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 + Norway, Switzerland, Turkey	**88651**	**1475**	**51**

5.5 *Pumped Hydro Electricity Storage*

Table 9: Installed PHES power in Europe (Source: [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 + Norway, Switzerland, Turkey	**51,008 MW**	**5,859 MW**