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Synergies in the integration of energy networks for electricity, gas, heating and cooling

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Executive summary

Steadily increasing power consumption and ambitious climate protection targets require new approaches for energy supplying structures. Among developments regarding increased energy efficiencies of specific technologies, promotion of renewables and emission-free sources new solutions for a secure electricity, gas, heating and cooling provision must be found. The concept of a hybrid network endorses the utilization of interdependencies between different energy carriers and the corresponding technologies leading to synergy effects, which can have a significant impact on an energy system. The provision of flexible interconnectivity allowing load shifts in time and bridging the spatial discrepancy between energy supply and demand by smart grids will become essential for establishing an efficient hybrid network. Furthermore the hereby associated control and regulatory mechanisms as well as the required holistic approach for storage illustrate the complexity of an energy system in the future.

Transformation of the energy sector to efficiency and climate protection

The increasing demand for energy services in conjunction with extensive climate protection targets requires significant changes within the European energy sector. Consequently, a continuous transition from conventional and fossil fuelled power generation to low-carbon or even carbon-free generation is expected in the power supply structure of Europe over the coming years. However, the increasing contribution of renewable energy sources (RES), such as wind and solar, are subject to the specific characteristics of these sources, in particular to weather fluctuations as well as forecast errors, which lead to a volatile and intermittent power supply. Furthermore, the growing share of de-centralized electricity generation leads to new grid structures with multidirectional flows of energy. Grid operation is therefore more complex and congestions within the transmission network result. Suitable measures such as flexible generation, energy storage and load management must be found to provide a secure balance between energy demand and supply.

Interacting networks and technologies

Mitigating climate change requires not only an increase in energy savings but also the promotion of progressive clean energy technologies in the electricity sector but also in the gas, heating and cooling sectors. The integration of the different energy networks, so called hybrid networks, provide a potential solution for these energy supply challenges. The main goal of interacting networks is to cope with the demand, while achieving emission savings and establishing an efficient and flexible energy system. It describes a multi-functional energy system which utilizes the synergies of different technologies and energy forms by

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optimizing their interactions in operation and to achieve a secure supply.

The efficient conversion of different energy forms, as well as the storage and transport of energy carriers, has great potential to increase flexibility and stability within the energy system. In addition, an intelligent implementation of storage or transportation processes can help to avoid shedding of fluctuating renewables and thus lead to reduced system costs. It is evident, that the "system intelligence" in this cross-domain network energy system is of great importance. A deeper integration of alternative energy forms can be a promising option for the stability of the energy system. For example, coupling the available electricity, gas, heating and cooling networks through Information and Communication Technologies (ICTs) can conduct a variety of options, which yield a more flexible, sustainable, reliable and economical energy system.

Therefore, the coordination of energy transport, distribution, storage and use with ICTs are crucial aspects of a well-functioning hybrid network. The complex interdependencies between different energy carriers and the variety of available technologies require solutions adapted to local conditions. Figure 1 presents a possible approach of an integrated hybrid energy network.

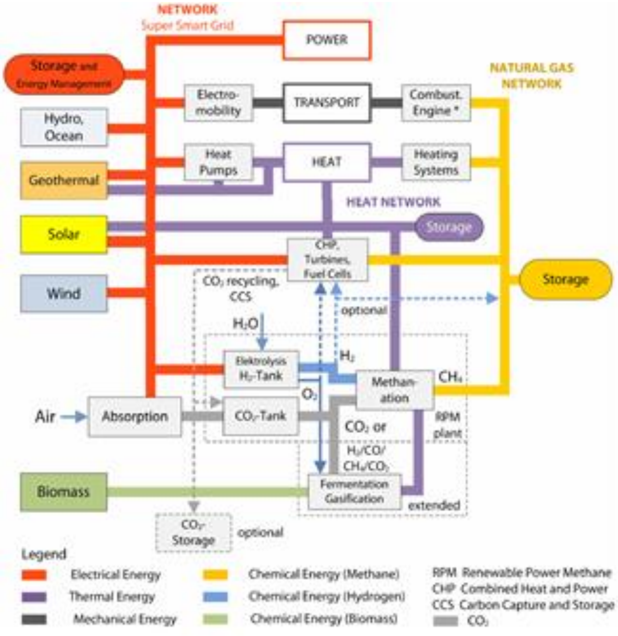

Figure 1: Conceivable design of an integrated energy network system[1]

As the number of installed photovoltaic systems, wind turbines and other RES grow, the requirements on the electricity grid increase due to intermittent feed-in. Furthermore, modern technologies like heat pumps have gained strong acceptance in the residential heating sector due to their high efficiency and flexibility. In this regard, significant improvements on energy demand reductions and overall emission savings can be achieved. Currently about 175 TWh of electricity is used per year to cover 7% of the total domestic heating demand in Europe[2]. The vast majority of this share is supplied by inefficient resistive electric heating. Today heat pumps become with coefficients of performance (COP) around 3 increasingly important for efficient heat supply and it is assumed to reach average COP levels of about 4 by 2050. This way primary energy savings of up to 75% compared to resistive electric heating can be obtained. Furthermore a shift from gas and oil based heating to RES powered heating pumps can help with the realization in achieving a widespread decarbonisation of heating supply[2]. Based on the technological targets of studies[3] the installed capacity of heat pumps can reach 35.6 GW_{th} by 2020 in the EU 27 and provide 191.6 TWh_{th} for heating and warm-water supply per year.

The thermodynamically efficient use of fossil fuels in energy conversion processes to minimize overall losses is an important aspect for reducing CO_2 emissions. For instance, combined heat and power units (CHP), enable higher overall efficiencies (around 60-85% depending on the power to heat ratio) than traditional power plants due to the simultaneous electricity and heat production. Cogeneration units are bound to either heat-controlled operation, where heat output is adjusted according to the thermal energy demand of the consumer, or power-controlled operation, where power output is determined by the demand for electricity. In the case of heat-controlled CHP units a more flexible operation at better load-points, and thus a further reduction in the carbon footprint, are feasible through integration in a hybrid network with district heating. This way electricity is produced

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[1] Sterner, 'Bioenergy and renewable power methane in integrated 100% renewable energy systems', Dissertation, University of Kassel, 2009

[2] 'Roadmap 2050 – A practical guide to a prosperous, low-carbon Europe, Technical Analysis', April 2010, http://www.roadmap2050.eu

[3] http://www.ehpa.org

at high efficiency and surplus heat can be stored leading to a possible decoupling of supply and demand. CHP systems in commercial[4] and residential[5] buildings can reduce emissions of CO_2 equivalents by 15-26%. An extension of the CHP process is referred to as trigeneration or combined cooling, heat and power (CCHP). In CCHP the combination of a CHP unit with an absorption refrigeration system allows the utilization of excess heat for useful means, e.g. due to seasonal demands or in industrial processes. Studies show a potential reduction of CO_2 emissions by 65–80% per kWh of useful energy output based on trigeneration compared to separate generation[5]. Also, the wide variety of these co- and trigeneration units allows for a greater market penetration. Customizable applications to specific consumer needs regarding heating, cooling and power demand eventually lead to an increasing number of installed micro CHP and CCHP plants as a de-centralized energy supply in local buildings. This increases the tendency of a further reversed feed-in from de-centralized generation units and promotes the concept of energy producing consumers – "prosumers"[6].

Smart grids, information and communication technologies of a modern energy system design of the future

Through intelligent interconnections of different technologies and energy networks reductions in overall energy consumption can be obtained. In this context, smart metering is often mentioned in combination with ICT and different approaches for sensoring or metering devices exist. Metering devices in households can consist of simple displays showing current energy demand to the users, which are already available and easy to implement. This can be one way to have an effect on consumers' behaviour by increasing awareness. Field studies[7] have shown that users, who are able to evaluate the relevant information shown on such passive meters can adjust their consumption behaviour and realize reductions in, e.g., electricity consumption of up to 10%. Another possible passively operating approach is the communication of acquired big data to centralized energy providers for specific consumer behaviour studies. Due to high feed-in it can become necessary to stabilize the distribution network through external influencing of power demand via short-term demand-side-management (DSM), e.g., during higher solar energy output as predicted. Actively operating ICTs can access electric devices in a household, e.g., washing machines or dryers, and regulate energy consumption and realize load-shifting based on the current grid status.[6] Through this approach, 5-10% of the installed capacity in households and at certain times with very high incentives even more (10-30%) can be deferred for a minimum of one hour. Even higher load-shift potentials are acquirable in the industrial sector[7]. Further demand flexibilities can be activated by battery storages in electric vehicles, heat pumps, storage heaters, dishwashers and cooling equipment including air conditioners and refrigeration systems[9]. Altogether the potential for the temporal increase of loads by DSM in all EU countries including Norway and Switzerland is forecasted to increase to 25 GW by 2020. The potential for interim load decreases is even higher (40 GW) and the total shiftable load potential amounts to 560 TWh per year. These potentials are only acquirable with intelligent ICT and overall cross-domain networks[8]. The possible structure of an intelligent power system according to E-Energy is shown in Figure 2. The energy supply system combined with an information system form an intelligent energy supply system, which is often referred to as smart grid. Based on this basic infrastructure new market and grid functions can develop, which then contribute in form of energy services to the overall intelligent energy system. Therefore the energy information system consists of an automation system for the different networks as well as a service platform with standardized and protected information technologies[9].

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[4] Mago, Smith, 'Evaluation of the potential emissions reductions from the use of CHP systems in different commercial buildings', Building and Environment, 2012

[5] Elsarrag, Alhorr, 'Optimisation of CCHP and biomass heating for maximum CO_2 reduction in a mixed-use development', Green building practices, 2013

[6] Energy Technology Perspective 2014, IEA

[7] Karg, Kleine-Hegemann, Wedler, Jahn, 'E-Energy Final Report', B.A.U.M. Concult GmbH, Munich/Berlin, 2014

[8] Grote, Drees, Budke, Moser, 'Einfluss des Demand Side Managements auf den Kraftwerkeinsatz in Europa', ET 12/2013

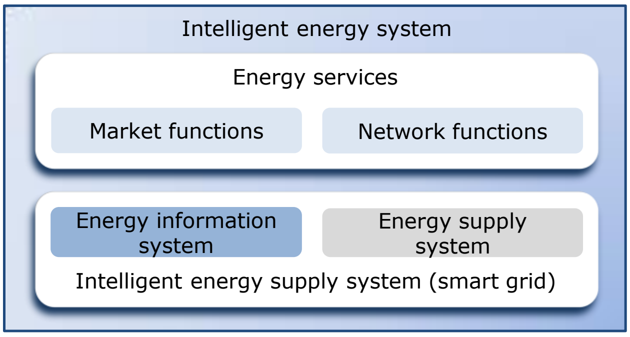

Figure 2: General structure of an intelligent energy distribution system[9]

The architecture of a modern energy system with a smart grid can be divided into various layers, corresponding to its functions[10]. The hardware components like smart meters and sensors form the foundation for the information and communication tools. Next a platform for information exchange between the market participants needs to be established. The acquired data from sensors at centralized and de-centralized generation units as well as from consumers' side must be gathered and processed in big data models. Another important layer of the overall design is responsible for the system security. Therefore, a database with possible scenarios, logical functions and protocols needs to be defined and followed in order to maintain a working energy market. Finally the business layer centralizes the possible market design, business models of participants and contains the political and regulatory framework. All these different parts of an intelligent energy system have to be synchronised and carefully coordinated so that the expectations of the market are satisfied[10]. Establishing and running such multi-layer infrastructure composes a high systemic responsibility. The discussion about who should adopt this new role and bear the responsibility within the energy sector is not yet completed. An option, which is often mentioned in this context, is the expansion of the distribution system operators' functions[9].

Through economic incentives all network users and stakeholders of the holistic energy system should be involved into the provision of ancillary services. That means the regulatory framework includes measures for the allocation of network connection and usage charges in accordance with the principle of causality and yet allows for a solidary energy market design for producers and consumers[9]. Furthermore remuneration of flexibility and adherence to power plant schedule on generation side as well as remuneration of flexibility on demand side via tariffs or shift options should be implemented. Prosumer behaviour in the context of management of de-centralized generation units is also an important factor, which needs to be yielded in regulations. For certain aspects governance is required and limits to market mechanisms need to be identified and depicted to prevent impediments for the implementation of social goals like system security, strategic capacity reserves and implications on other energy systems[9]. The technology readiness level (TRL) for ICT based DSM, smart markets and intelligent grid management vary widely for different regions in the EU[11]. Nevertheless some regions are being considered to have reached a TRL of 6 (on a scale to 9) in the context of intelligent energy systems and ICT in smart grids. Studies predict some regions will reach TRL 8-9 by 2020[11].

Mobility sector and energy storage mechanisms

The implementation of a smart grid concept and a sustainable energy supply consists of more than one technology or RES. Furthermore a gradual and evolutionary transition of the existing energy system towards an interconnected network require not only complete and efficient integration of RES but further synergies can be achieved through integration of the mobility and transportation sector. Beside solar and wind power a developing RES is biomass, which can either be used directly in a combustion process for electricity and heat production or indirectly after converting it to other forms such as biogenic fuels. Biomass to liquids processes and cellulosic ethanol are still in the development stage but may become a promising, CO_2 emission saving complement to fossil fuels in the future mobility sector. The utilization of biofuels can lead to well-to-wheel emissions of 20 - 80 g CO_2/km (dependant on the fuel pathway) compared to 100 - 200 g CO_2/km for an average gasoline car. Highest reductions can be achieved by so-called second-generation biofuels which are currently in the process of development, e. g.

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[9] E-Energy, 'Smart Energy made in Germany', final report 2014, http://www.e-energy.de

[10] Siemens Infrastructure & Cities Sector / Smart Grid Division, Press Release, 2012 May 11th

[11] Brunner et al., 'Mapping & Gap Analysis of current European Smart Grids Projects', SmartGrids ERA-Net Report, April 2012

ethanol based on lignocellulose, biomass-to-liquid fuels or algal biofuels like biodiesel. The relatively minor necessary changes regarding the fuel distribution infrastructure and powertrain make second-generation biofuels an attractive research field for the automobile industry acquirable in the near future. The implementation of hydrogen-based technologies in the mobility sector is conceivable till 2050 though requires extensive infrastructure upgrades[12].

The increasing utilization of electricity for providing mobility services is another promising option for reducing the carbon emissions in the transport sector. The current low market penetration of electric vehicles can be ascribed to consumers' aversion, e.g., due to higher prices for electric vehicles, lack of effective incentives like price modelling and a high dependency on political regulations. However, government initiated subsidy programs (e.g., in Norway and China)[13] can counteract such aversion. Prospective improvements regarding battery costs and production processes will make electric vehicles more competitive and will lead to rising numbers of electric and grid-supplied hybrid vehicles. This makes the intelligent integration of electric vehicles into the grid an essential part of an advanced energy system. The inclusion of batteries for possibly electric storage as well as charging control can support load management as a cost-effective measure for demand-side-management at the consumer level[14].

Benefits of electric storage based on batteries like those in electric vehicles or supercapacitors are evident in their modular structure and thus simple expandability as well as their high flexibility. The superior responsiveness allows immediate grid frequency regulation in case of fluctuations. Nevertheless, high manufacturing costs of lithium-ion batteries of 600-2500 €/kWh and benefits of alternative technologies have outweighed these advantages so far. The long-term goal is to cut manufacturing costs to 250 €/kWh until 2050[15]. Currently, pumped hydro storage remains the most established technology for utility-scale electricity storage due to its flexibility and efficiency of around 75-80%. However, the construction of pumped hydro storage requires specific topographical characteristics with reasonable elevation differences between reservoirs. Also, high construction costs and concerns regarding environmental disruptions, like alterations to the natural river course and its impact on terrestrial wildlife habitats, limits the realizable potential[16].

In addition to electric energy storage, thermal energy storage can be integrated in an efficient energy system. Surplus heat from solar collectors or waste heat from industrial processes for example, can be stored and supplied when needed. Seasonal storage can bridge periods between supply and demand for up to several months at efficiencies of 50-90% depending on storage time. Thermal storage can be built as sensible heat storage containing water or other mediums but also as latent heat storage utilizing a phase-change-material like special salts. The variety of seasonal thermal energy storage options covers a large spectrum of possible applications in single residential buildings up to large building complexes and community district heating networks. This allows an intelligent and flexible integration in a hybrid network. Besides the ability to temporally shift heat generation and demand, thermal energy storage provides a basis for improved efficiency in an application to power units where waste or surplus heat is available. Therefore, an interesting approach to the integration of thermal energy storage can be conducted in combination with electricity-controlled cogeneration units. Those generation facilities can thus be operated independently of heat demand at more efficient load levels. Fuel utilization in heat-and-power units can thus be improved in this context[17].

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[12] Rausch, Kiennemann, Sauciuc, The Role of Catalysis for the Sustainable Production of Bio-fuels and Bio-Chemicals, 2013, pp. 397-443

[13] Motavalli, 'China to Start Pilot Program, Providing Subsidies for Electric Cars and Hybrids', New York Times, 02.06.2010; Avere, 'Norwegian Parliament extends electric car initiatives until 2018', 2012

[14] Napierala et al., 'Investigation of Electric Vehicle Grid Support Capability', Energy Procedia Volume 46, 2014

[15] Taylor et al., 'Pathways for energy storage in the UK'. The Centre for Low Carbon Futures 2011

[16] Gimeno-Gutiérrez, Lacal-Arántegui, 'Assessment of the European potential for pumped hydropower energy storage, JRC Scientific and Policy Reports, 2013, pp.5-6

[17] Smith, Mago, Fumo, 'Benefits of thermal energy storage option combined with CHP system for different commercial building types', Sustainable Energy Technologies and Assessments, 2012

Energy storage mechanisms based on power-to-x technologies

Power-to-gas technology (PtG) is a promising path to help solve the challenges regarding electricity and seasonal storage and to regulate grid capacity utilization in case of congestions. This can be achieved by converting surplus power from RES into methane gas in a two-step process by producing hydrogen via electrolysis and through addition of carbon dioxide in a methanation process. The efficiency achieved during electrolysis is currently highly dependent on the system size and varies between 60 and 80%. Alkaline water electrolysis systems are already technically mature and commercially available at module level. The electric power input ranges from few kW up to a limit of 5 MW. The modules can be operated at part loads from 20 to 40% and it is possible to operate the individual modules in parallel mode for larger power range coverage[1]. Similar values apply for polymer electrolyte membrane electrolysis. High temperature electrolysis systems are still at basic research levels, however, it is expected that those are of limited use in dynamic operations[18]. The optionally following methanation process has an efficiency of between 75 and 85% and is thus detrimental to the efficiency conversion chain. The overall efficiency for the generation of methane provides values between 46 and 75% (average 63%). The indicated efficiencies of the methanation are based on the assumption that excess CO_2, for example from biogas plants or carbon capture and storage facilities (CCS) is available. If for methanation atmospheric CO_2 is used the efficiency of PtG is again significantly reduced to an average of 48%[1]. The resulting methane gas can then be fed into the gas grid. Another option is the direct feed-in of hydrogen into the gas network without methanation. However, currently the maximum share is limited to 5 vol% (2 vol% for certain application, e.g., transport fuel). An increase of the hydrogen share beyond 10 vol% in the gas network is not feasible without major altering of the installed technology and high investment costs[19]. Despite the limited efficiency due to conversion losses the power-to-gas technology can be an efficient approach for large seasonal storages in a holistic energy system in the future and provide a way for balancing fluctuating renewable electricity generation. Furthermore the existing storage and pipeline capacities for gas in the EU 27 exceed with 94 bcm[20] by far the storage capacities in the power network. Few PtG plants are already in operation but lack economic feasibility for a wide commercial use. Thus, reliable predictions for a future market penetration of this technology are currently not available and depended on technological advances and economic incentives.

Further utilization of methane produced in a PtG process can then be handled according to the specific consumer needs, such as electricity, heat or mobility. Different energy conversion chains for methane are necessary based on the respective energy service demand. Therefore low efficiencies of conversion approaches do not automatically implicate the inferiority of the described process. However, from a holistic perspective it should be sought to pursue the paths which allow maximum energy use and high flexibility in an energy system[23].

In the mobility sector methane can be utilized as a fuel in form of compressed natural gas (CNG) for combustion engines. Hence, this approach connects the power and mobility sector indirectly. In the EU and EFTA the current annual methane consumption by combustion engines in vehicles adds up to 2.78 bcm in 2012[21]. Depending on the future market penetration of CNG fuelled vehicles the natural gas demand in the transport sector may vary. Nevertheless conservative studies forecast a projected consumption of 11.7 bcm in 2020 and 16.5 bcm by 2025 of natural gas in the mobility sector[21]. The transport sector currently accounts for 0.5% of total natural gas demand in the EU 27 and this share is forecasted to increase to 2.4% in 2020 and reach 3.2% by 2025[22].

One way for utilization of the synthetically generated gas in the energy sector can be the application in open cycle gas turbine power plants. The Overall efficiency of the power-to-gas-to-power chain is considered to range from 19-45%[1,23] including all conversion losses. Through this path around 30% of the originally acquired electricity can be stored in form of gas and regained at a different point of time. The application of gas in

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[18] http://www.netzentwicklungsplan.de, 'Netzentwicklungsplan Strom 2012', pp.33-35

[19] Melaina, Antonia, Penev, 'Blending Hydrogen into Natural Gas Pipeline Networks', NREL, 2013

[20] http://www.gie.eu.com

[21] Rogers, 'The Prospects for Natural Gas as a Transport Fuel in Europe', Oxford Institute for Energy Studies, p.41, March 2014

[22] World Energy Outlook 2013, IEA, pp. 102-107

CHP plants lowers in most cases the electrical efficiency compared to large gas turbines, however the utilization of waste heat allows for a higher overall efficiency of the power-to-gas-to-heat & power chain, which can reach an efficiency of 44% with total outputs consisting of electricity and usable heat[1,23]. Another option can be the utilization of gas for heating purposes. Including boiler conversion losses through this approach 50-55% of the originally excess electricity can be utilized, e.g., in district heating networks or warm water supply[1,23].

Another example for integration of the electricity and heat market is the power-to-heat path. Whereas the possibility for interim energy storage in form of gas is in this case removed, yet almost loss free conversion between electricity and heat can be achieved. This approach can replace fuel-based CHP units with electric heaters in periods of high heating demand that coincide with surplus electricity feed-in from RES. The most common utilization of power-to-heat is the domestic hot water supply, via a heating rod. This can help save primary energy sources through avoidance of renewables shedding without the application of additional storage mechanisms but a hot-water tank. In addition an integration of the existing night storage heater infrastructure in combination with ICT is conceivable[24]. The market potential for such smart electric thermal storages based on the total installed capacity of conventional night storage heaters amounts to 37 GW in the EU 27 by 2050. Furthermore the utilization of fixed electric heaters' capacity corresponds to 94 GW of possibly accessible load. Including hot water cylinders with an estimated potential of 18 GW the total variable load sums up to 149 GW in the EU 27 by the year 2050. The latter application allows for a year-round availability. Again, such power-to-x technology approaches require intelligent control mechanism based on ICT[24].

Carbon capture and storage

The production of natural gas during methanation in power-to-gas processes requires the utilization of concentrated CO_2. The carbon capture and storage technology (CCS) is also an approach which varies from the presented methods to decrease CO_2 emissions that result from the use of fossil energy sources in power generation and various industries is the process of capturing waste carbon dioxide from large emitters and depositing it in geological formations. The injection of CO_2 into underground storage sites has been conducted in the past, e.g., for enhanced oil recovery[25]. However the long-term impact on the environment and technical feasibility of systematic storage of CO_2 is not fully explored yet[6]. The future of CCS in Europe is to date unclear partly due to its presently high implementation costs and the failure of financing mechanisms (NER300) linked to the European emissions trade system (EU ETS) and the current low prices of CO_2. Provided the timely introduction of transitional support measures CCS could contribute to 222 Mt of CO_2 reductions per year in the EU by 2030 – the equivalent of 4% of the EU's greenhouse gas reductions commitment effort. Largest contribution to this goal can be achieved through integration of CCS in the power sector, e.g., at large coal power plant locations or within the heavy industry sector, where it can be utilized in PtG methanation processes when needed. The specific efficiency losses depend on the type of fuel and boiler as well as the strategy of carbon separation, which is used. The correlated decrease in efficiency of 5-10 percentage points, e.g., in power plants with oxy-fuel combustion compared to conventional plants, results from the additional energy input needed for the upstream oxygen separation[26]. Similar values are listed for pre- and post-combustion processes for capturing CO_2. Nevertheless, CCS can be efficient from an economic point of view, depending on the CO_2 costs at the EU ETS. Prices at 35-60 €/ton CO_2 are considered to form the current break-even point of CCS. The main part of the carbon storage capacities in Europe is located in the North Sea, such as the Utsira basin. Its storage capacity is being estimated at about 42 Gt CO_2 and its accessibility to a number of countries can increase cost-effectiveness of CCS. Nevertheless the transport of CO_2 to the North Sea would require large investments into the CO_2 pipeline infrastructure. The costs for CO_2 transport and storage in this area are estimated at 5-

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[23] Appelrath, Lehnhoff, Rohjans, König, 'Hybridnetze für die Eneriewende-Forschungsfragen aus Sicht der IKT', acatech, 2012

[24] Raadschelders, Sikkema, Groen, 'Potential of Smart Electric Thermal Storage Contributing to a low carbon energy system', DNV KEMA Energy & Sustainability, 2013

[25] Statoil's Sleipner, Snohvit projects; BP's In Salah project

[26] Tom Kober, 'Energiewirtschaftliche Anforderungen an neue fossil befeurte Kraftwerke mit CO_2-Abscheidung im liberalisierten europäischen Elektrizitätsmarkt', FB 117, IER University Stuttgart, 2014

11 €/t CO_2, depending on the distance to cover, at a maximum annual injection rate of 150 Mt CO_2. The transport infrastructure will require an additional construction of an estimated 22,000 km long network of pipelines until 2050 to the destination caverns. This will be strongly dependant on the success of international cross-border co-operation[27]. Also, the legal requirements for CO_2 transport, storage monitoring and verification for the licensing procedures need to be settled. From a technical point of view the TRL of CCS is considered to range at 6-7. Individual CCS chain parts as capture-transportation-storage are already operating at full scale worldwide. All together the global CCS Institute lists currently 21 active sites for CCS with a total injection rate of 31 Mt CO_2/a, out of which two (Snohvit and Sleipner) operate in Europe[28]. Nevertheless, further technological progress in the field of CCS research is needed to properly assess long-term risks and to allow a cost-effective implementation of solutions in the industry politically initiated financial incentives may be necessary[29]. With proper support mechanisms the commercial availability for all chains of this technology and the establishment of full-scale CCS projects in Europe is expected by 2020[28].

Conclusion

The variety of technologies and their different fields of application illustrate the complexity of an efficient energy system, where various energy forms, generation units and networks interact to promote synergies between each other. Each pathway raises the fundamental question of how the corresponding infrastructures can be smartly linked to achieve an efficient, economic and climate friendly energy system. However, direct comparisons between different systems and their performance should be handled cautiously. Characteristic aspects of energy conversion processes, storage potentials and possible improvements of considered technologies must be taken into account. Efficient energy systems should always be designed and adjusted to a specific region based on local conditions. The emphasis should be placed on adaptable technologies, which promote flexibility and integration of new solutions into the system in a holistic approach, e.g., CHP with seasonal storage.

→ The development of the energy sector requires a locally and temporally differentiated adaptation or evolution of the energy system. The necessary investments must be encouraged through a change of the conventional business models within the energy industry and the provision of new market designs. Thus, a reliable, financially predictable framework for new business models must be established. In order to create planning security for the economy, clear political signals are necessary. The transformation of the energy system as a strategic, societal task, which is jointly financed is an important message to be communicated.

Efficient solutions for the successful integration of small, de-centralized generation units need to be found. The provision of flexible interconnectivity to allow load shifts in time and space by smart grids and associated control and regulatory mechanisms are necessary, since an increasing number of decentralized and independently operating units complicate proper grid management. Currently, the various available storage technologies such as electric, thermal and power-to-x storages are at different development stages. They are thus characterized by high diversity of cost and competitiveness. Hence, the exact role of certain storage concepts in an energy system will also emerge with the respective development trends.

→ The EU should continue promoting scientific research, innovations and developments of different storage technologies. Further liberalization, harmonization and coordination of the European energy markets, diversification of energy sources and supply routes, as well as diversification of external energy relations will reduce the import dependencies and allow for maintaining a high security of energy supply.

In the long-term, it is essential to broaden the notion of a secure and efficient energy supply to include electric, chemical and thermal energy carriers into hybrid networks. ICT and artificial intelligence will become necessary to support the integration of RES technically and economically into

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[27] Strachan et al., 'CCS in the North Sea region: A comparison on the cost-efectiveness of storing CO_2 in the Utsira formation at regional and national scales', International Journal of Grennhouse Gas Control, 2011

[28] http://www.globalccsinstitute.com, July 2014

[29] Lupion, Herzog, 'NER300: Lessons learnt in attempting to secure CCS projects in Europe', International Journal of Greenhouse Gas Control, Volume 19, November 2013, pp. 19–25

the overall energy system. Only with ICT it will be possible to converge the large and mainly independently operating networks for electricity, heat, gas and mobility into hybrid networks or poly-energy grids. De-centralized CHP and CCHP units are examples for the progressing development of energy systems that integrate electricity, gas, and heating and cooling energy networks. In a modern supply system these must not be optimized separately but simultaneously in order to utilize the synergies by promoting interactions among energy carriers. This can be realized by loss reductions during energy conversion processes due to utilization of waste energy, e.g., in CHP / CCHP units and better integration of RES in the energy system. Also, the different networks can be used for short-term storage purposes, e.g., by coordinating power-to-heat units during periods of high RES feed-in and district heating. Hence, the efficient management of the interdependencies between the different networks will be of major importance in the future. Here, new solutions for an open information exchange and communication (smart energy grids with sensors, big data transmission and monitoring technologies) also become essential.

→ Important contributions to overall energy system efficiency gains must be achieved on network distribution level. Increased penetration with ICT infrastructure is a prerequisite for coordination processes that are necessary for a higher transparency. Also, the acceptance of flexible consumption and smart grids can only be achieved through general education (beyond consumer communication of energy suppliers) and economic interests. The acceptance depends on balanced data protection and adequate benefit effects.

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