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Qualitative Analysis of Strategies for the Integration of Renewable Energies in the Electricity Grid

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Abstract

Solar and wind electricity production with their volatile production patterns, have a high proportion in the renewable electricity production in the target frame of the German "Energiewende". The ratio of secure to non-secure generation capacity will increase to almost 1:1 in the year 2020 and thus further worsen the already existing problems in the integration of renewables into the grid. The consequence will be higher overall electricity supply costs. Solution options for this are grid expansion, more flexible generation in conventional power plants and demand-side control such as smart grids or smart markets. The latter offer rewarding capacities, especially in the heat demand. Although combined heat and power units (CHP) can be used as a flexible, decentralized generation capacity, they have to be linked up and integrated accordingly. The need for flexible generation and balancing power requires additional energy storage. Next to pump storage facilities wind-hydrogen systems or stationary battery storage systems offer solutions to medium and large amounts electricity absorption and reinstate feeding into the grid. Due to the developments status of all these options, an appropriate regulatory framework for the market introduction is needed.

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1. Challenges of the German "Energiewende"

Global efforts to reduce greenhouse gas emissions have led to the adoption of a series of climate protection programs in Germany and elsewhere in Europe. In this context the German federal government passed its "Energy Concept 2050" in 2010 [1], setting the goal to achieve a 35 % share of renewables in gross electricity production until 2020.

This paradigm shift in energy production - away from a centralized and predictable generation towards a decentralized, often little predictable and non-persistent production - confronts the mature system with major challenges. An increasing share of RES in the electricity generation leads to a growing gap between production and consumption.

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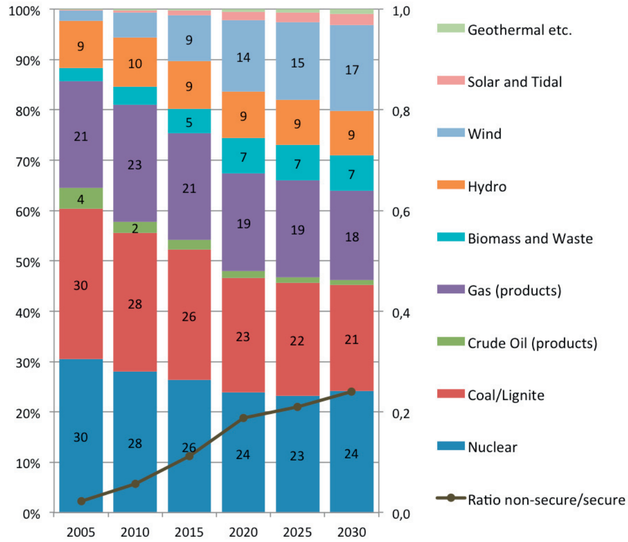

Fig. 1. Development of different generation sources in the gross electricity generation (quantity comparison) in Europe in the years 2005-2030 in the frame of the ”Reference scenario” of the European Commission; left ordinate share of total electricity generation, right ordinate ratio of the amount of electricity generated from non-secure sources (wind, PV) and the production of secure sources [3; own calculations]

Ultimately, this will cause problems in the adequate provision of energy for consumers in terms of time and volume. This effect is worsen by the reduction and decreasing economical operation of conventional power plants.

Following the Fukushima nuclear reactor accident in 2011, the German government decided to accelerate the already ongoing phase-out of nuclear power production [2]. Previously existing plans with respect to available generation capacity had to be adjusted again. The henceforth large-scale remodelling process on all levels of energy supply carries a great deal of opportunities but also risks since horizontally and vertically highly integrated systems need to be adapted to these new structures. The from the political environment introduced term ”Energiewende” indicates the dimension and scope of this measures. This paper quantifies the extent of the problem and presents possible solutions with which both electricity shortages as well as unusable oversupplies could be avoided.

2. Development of generation capacity

Possible developments and changes in the power generation of the coming decades are typically based on scenarios. These are desired development paths based on a defined set of conditions and factors, while in contrast to this forecasting tries to predict the market development based on probability. The following scenarios draw two substantially different pictures for Europe (EU27) and for Germany.

Fig. 1 is based on the latest developing analysis ”EU Energy Trends to 2030”, regularly conducted by the European Commission [3]. The policy based approach takes into account regulatory requirements and the associated economic framework for the future mix of power plant types. The study was fundamentally revised in 2009 in the light of the European recession and updated to take into account lower economic growth rates as well as better energy efficiency.

The ”2009 Baseline” scenario predicts the European energy production (quantity comparison) taking into account existing guidelines and regulations e.g. emission trading or efficiency measurements. Objectives concerning the share of RES in the EU are not included. By contrast the presented ”Reference” scenario describes the possible development with the involvement of these targets. A commonality of both scenarios is a strong increase of renewables in the energy mix, especially wind power. However, the share of solar power is relatively low in both scenarios, since within the period of analysis the positive development of investment costs and efficiency has not been considered [4].

Within the conventional sector, coal and lignite lose market shares despite the inclusion of Carbon Capture and Storage (CCS) in the simulations. This is due to a decrease in fossil energy consumption, which is mainly at the

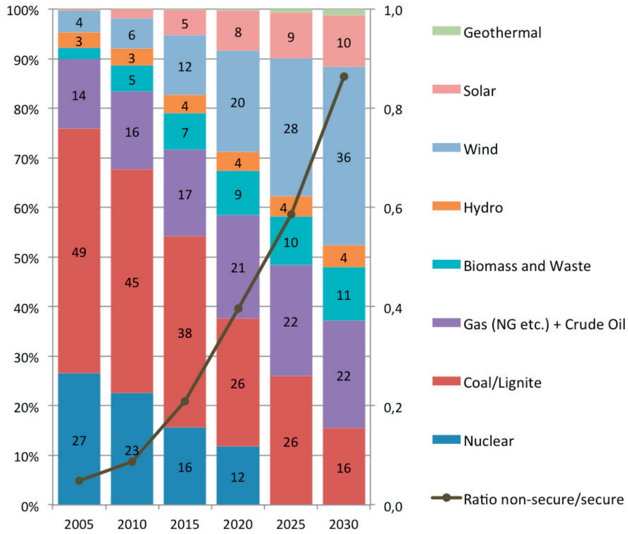

Fig. 2. Development of different generation sources in gross electricity generation (quantity comparison) in Germany in the years 2005-2030 in the scenario 2011-A of the Federal Ministry for the Environment [5; own calculations]; axis explanation see Fig. 1

expense of solid fuels and only to a small extent at the expense of gas and nuclear energy. While gas-fired plants are still needed as balancing power, nuclear power plants are still long-term base load capacity for several European countries. However, it should be noted, that the presented scenarios are not yet adopted to some country's nuclear phase-out plans after the Fukushima accident in March 2011. This relates in particular to the countries of Germany (exit 2022), Switzerland (exit 2034), Belgium (exit 2025) and France (reduction from 2012). It is likely that these decisions will accelerate the growth trend of the renewables, because the reversion to fossil fuels such as coal is not a cost-effective alternative: even though the emission trading scheme is not yet an effective control element, the associated emission limits (”emission cap”) can become an economically burdensome factor for conventional power producers. The comparison of both scenarios (2009-Baseline/Reference) also shows that, despite different assumptions in their calculation, the existing legal framework has already been developed so far, that relatively homogeneous results for future generation capacities and the share of RES are produced.

Germany, in comparison, features a much higher penetration of RES its generation portfolio as a result of the aforementioned ambitious goals of the federal government for RES expansion [Fig. 2].

Again, coal and lignite lose market shares. Moreover, the successive reduction of nuclear energy in the power portfolio until the year 2022 reduces the overall conventional share. These production levels are compensated by a massive expansion of wind energy. This is accompanied by a significant increase of photovoltaic and the use of gas-fired power plants, which can react far better to fluctuations in demand due to their flexible production.

From a network operator's perspective the main question to answer is which technologies with their specific production characteristics come into play in the near future since this will determine the demand for ancillary services. Both Fig. 1 and Fig. 2 display the ratio of secure to non-secure amounts of electricity production in GWh. In this context, non-secure applies to wind and solar energy. In the EU this ratio will be at around 0.25 by 2030 (i.e. four times as much securely generated electricity as non-secured electricity). In Germany, however, this figure rises to almost 0.9 in the same period. That would mean that every other kilowatt hour might need to be replaced by a fossil-fuelled power plant at short notice if the wind does not blow or the sun does not shine.

3. Fluctuating supply of renewable energy and associated challenges

The growth of renewable energies as well as the reduction of conventional power plants (nuclear power stations) leads to a change of the existing generation portfolio, which goes beyond the mere question of the CO_2-intensity of electricity production paths. The organization of energy supply in the previous decades with a few large producers was characterized by predictability and controllability, and made use of a central, unidirectional distribution from the producer to the consumers. The newly added, renewable generators change this organization significantly: they are often decentralized producers (PV, wind onshore) and are only partially predictable in both their production times as well as production quantities (offshore wind, PV, wind onshore). Only a smaller share of renewable production technologies such as hydropower, geothermal and biomass can be used for regular, scheduled electricity production. A third problem of the fluctuating production of most renewable energies is that, due to fewer production hours, the energy feed-in into the grid is very aggregated, meaning that a lot of electricity is being produced in few production hours rather than evenly distributed over time.

The integration of these fluctuating production patterns challenges the network operators. Currently, the transmission system operator has to ensure the stability of the network at all times and compensate for both the temporary oversupply of renewable electricity as well as the breaking away of such generation capacity.

Fig. 3 shows the wind energy forecast and real feed-in figures for the control area of the transmission system operator 50Hertz in autumn 2012. The graph depicts three examples of where the TSO had to intervene for the purposes of system stability. At that time this control area was the one with the highest installed wind power capacity in Germany. Intervention caused by PV remain out of consideration in this paper.

Example 1 shows a deviation of the actual production from the forecast. Today, wind forecasts are generally very accurate and can be taken into account when scheduling the operation of fossil-fuelled power plants. However, as can be seen in the figure, the anticipated wind energy feed-in starts half a day earlier than expected and is also more than 600 MW above the expected value. Such deviations have to be compensated by other - conventional - power plants. The more unexpected the deviation, the more the necessary intervention shifts from base-load power plants over medium-load power plants to, eventually, balancing power. Accordingly, the cost for the compensation of the faulty wind forecast increases. Moreover, if the deviation is substantial, the transmission system operator's limits in the provision of sufficient balancing power can be reached at some point.

Example 2 describes a greatly reduced production of wind energy due to a lack of wind (calm). Such downturns can last for several days and require a reliable power plant capacity as back-up. This capacity can either be provided by conventional power plants increasing their production capacity or, if those do not suffice, by activating cold reserves. In both cases highly redundant production systems are necessary, causing high fixed costs and little profit due the number of downtimes.

Example 3 features a sharp rise of wind power production in a short time period. The underlying data originate from October, when the autumn storms can bring the production to the capacity limit of the grid in a short time - in the depicted example wind power feed-in rises to 4,000 MW in the respective control area within a day, which equals the capacity of eight German lignite power plants. Such oversupply must be compensated by reducing conventional production capacities. Depending on the type of power plant, however, this process is limited to a minimum must run capacity of the power plant and a maximum power gradient per time unit. As in example 2, the profitability of conventional production diminishes if there is no monetary compensation in place for these system interventions.

Example 4 shows a situation in which the power supply from wind turbines exceeds the demand (= load) by private or industrial consumers during an autumn storm. Times of low demand, in which this effect is amplified, are night times for example (22 pm until 6 am). Since electricity from renewable sources has to be fed into to the power grid with priority according to the German Renewable Energy Sources Act (EEG §8 section 1) [6], the conventional electricity production reduces to a minimum. In addition, a buyer for the resulting wind power has to be found. Usually, the European electricity grid helps selling the energy to other countries in the EU. However, if no buyer for the electricity is found, the renewable generation facilities - lacking any large-scale storage - have to be throttled in their production, losing valuable renewable energy. In 2011, the amount of unused wind power was about 400 million kWh, which corresponds roughly to the yearly electricity consumption of 110,000 households [7].

4. Measures for the Integration of Renewable Energies

The previous chapter has shown that the qualitative structure of the generation capacity in Germany will change dramatically in the coming decades and is characterized by a growing share of fluctuating, renewable energy sources. Their generation patterns cause, under the current conditions, a number of problems for the integration into the existing

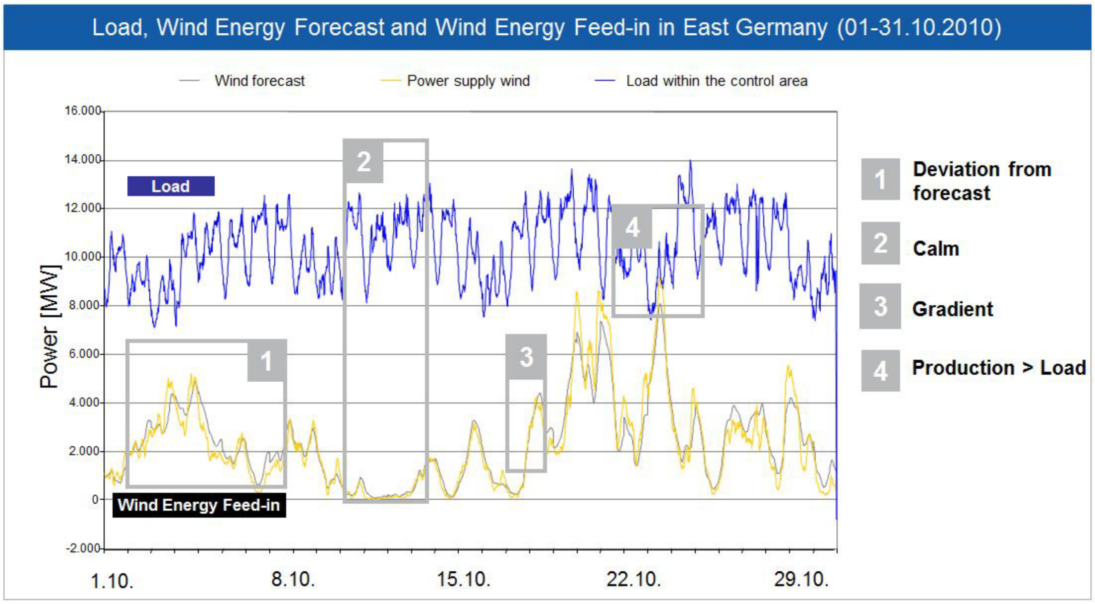

Fig. 3. Examples of problems resulting from wind energy fed into the German transmission grid. The figure presents the load curve from 01.-31. Oct. 2010 in the control area of 50Hertz Transmission (top, blue), the wind energy forecast at that time (bottom, gray) and the actual wind power feed-in (bottom, yellow) [7].

grid. The following strategies provide ways to integrate large amounts of renewable electricity at various grid levels, while at the same time guaranteeing the stability of the system.

4.1. Network expansion

From an economic point of view, network expansion is a cost-effective tool to ensure the integration of renewable energies in the German and the European electricity network in the future. The expansion of the transmission network is intended to ensure system stability and security of supply. In Germany, this process is coordinated by the Federal Network Agency (Bundesnetzagentur) since 2012. Its Network Development Plan (NDP) forms the basis of the network planning and takes into account the increasing supply by fluctuating generators. The NDP 2013 takes into account developments since the previous NDP in terms of the development of renewable energies and the political environment. The results are recommendations and measures for the network expansion on the basis of the calculated transmission needs. Currently, the transport of wind power from the North of Germany, where it is produced, to the South with its industrial demand centres, has priority. The required North-South capacity is increased by the optimization and reinforcement of existing cable routes over a length of 4,400 km. New routes are required over a length of 1,700 km (three-phase transmission lines) or 2,100 km (high voltage direct current lines). However, it is striking that at a projected demand of 44 GW transmission, the planned DC power lines in North-South direction have only a transmission capacity of 12 GW [8]. Over the next 10 years a total investment of approximately €21 billion for the development of the German transmission network is expected.

4.2. Flexible production of conventional power plants

So far conventional power plants, mainly hydro-thermal generation, are technically and economically optimized for the production of base load power with a high capacity factor. Due to the fluctuation of renewable energy, conventional generators have to become more flexible in their operation, resulting in higher requirements for hydro-thermal power plants. Thus, a transformation of base-, intermediate- and peak-load power plants into flexible production units needs

Year	Scenario data	lignite-fired PP	hard coal-fired PP	combined-cycle gas turbine PP	gas turbine PP	Unit
2011	*Basic*					
	Load gradient	1,3	2,0	2,0	10,0	%/min
	Must-run capacity	55	50	60	30	%
2023	*Cogeneration Optimised*					
	Load gradient	*	3,0	5,0	*	%/min
	Must-run capacity	45	30	20	*	%

* Not calculated in study

PP Power Plant

Fig. 4. Todays and future flexibility of power plants based on the generation type. Scenarios predict a lower must-run capacity as well as a higher load gradient during operation [13].

to be undertaken. Flexible operation, however, has its technical limits which are defined by the type of power plant and the technology "version" (i.e. age) in use [Fig. 4].

In theory, gas or combined cycle plants provide ideal conditions to operate at relatively high power gradients. On the other hand, increased power gradients to provide residual load, frequent ups and downs and a lower minimum load will reduce the service life of components, meaning that under current market conditions, the economic operation of hydro-thermal power plants is at risk. Consequently, regulations and business models need to be developed for power plants that provide essential ancillary services, helping them to operate economically even with low capacity factors. Under such conditions basically all hydro-thermal power plants may contribute to the solution of the future requirements such as a low minimum load, high load-gradients and short start-up times [cf. 9].

4.3. Load Management using Smart Grid and Smart Market approaches

Smart Grids and Smart Markets are defined as systems that provide communication elements in the power supply system. The objective is to facilitate the integration of volatile, usually demand independent renewable energies [10] by creating a smart, i.e. flexible, highly respondent market place. By providing real-time data from all energy levels it enables them to participate in the trade. Rules of the competitive market will avoid surpluses or shortfalls and reduce costly grid interventions (down-regulation of wind turbines in high winds without financial compensation) to a minimum.

For both Smart Grids and Smart Markets the following hypotheses can be derived:

- the design or the need for smart grid is dependent on the local production or load situation; the decisive factor is the interaction of generation, load, storage and grid
- Smart Grids in Germany are affected by the change from conventional to renewable generation and the trend towards decentralized generation
- the Smart Grid in the transmission network is characterized by increasing transmission capability and central storage; distribution networks must coordinate decentralized power producers and future load structures
- Smart Markets include flexible control of customer-owned power stations; to participate in the energy market a number of these smaller plants need to be aggregated in order to get sufficient "trading mass"

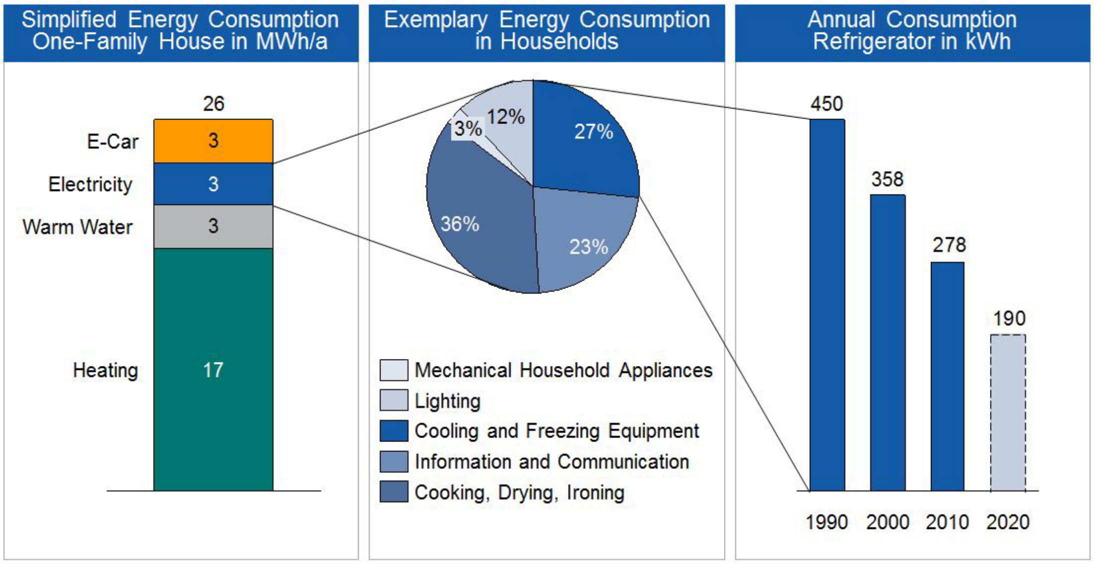

Fig. 5. Energy consumption and electrical loads in a standard German household, as well as their potential share of controllable elements in a smart grid [own figure].

Fig. 5 shows the total energy consumption - including heat supply, which is usually not provided by electricity - of an average German detached house with approximately 26 MWh energy demand per year. The greatest potential for load shifting is expected in the provision of heat (heat pumps, electric heaters, CHP). In the future, electric cars might add to this potential. In contrast, the control of electrical loads such as refrigerators offers a very low potential, which is even getting smaller over time due to energy efficiency improvements. If any of this potential should be deployed, though, consumers need to be electronically linked to the grid.

In the demonstration project ”Virtual Power Plant (VPP)” (2010-2013; consortium leader: Vattenfall Europe AG) a system was set up that provides heat mainly for households by applying Smart Grid/Smart Market tools. The VPP aggregates and controls a number of small CHP plants and heat pumps. As the ”smart” element in the system the algorithm behind the VPP is able to consider wind feed-in: In phases of little wind in the grid the decentralized CHP plants supply electricity back to the grid while the excess heat from the CHP is stored. Is there a high share of wind power in the grid, the decentralized heat pumps of the VPP use this electricity as a short-term activated load to store unrequired heat in the ground.

In 2012, more than 130,000 German households were supplied using this concept. In order to standardize the exchange of information, an industry group led by the utility Vattenfall developed an industry standard and a certification for distributed energy systems (”Virtual Heat & Power Ready” VHP-Ready). As a result certified systems can be integrated into the central control of the VPP without any further effort. This industry standard is constantly evolving, so that today for example battery storages can be integrated into the system.

5. Energy Storage

To stabilise the availability of the high proportion of non-secure generation, medium and long term energy storage must be increasingly used. In addition to the already economically viable pump storage power plants, technologies such as the batteries, a highly efficient compressed air energy storage and hydrogen systems are to be developed.

5.1. Pumped storage plants

Pumped storage plants are a mature technology for storing electrical energy. They have a high efficiency of 80% and can provide continuous power up to 10 hours. However, in addition to good scalability of approximately 50-1,000 MW

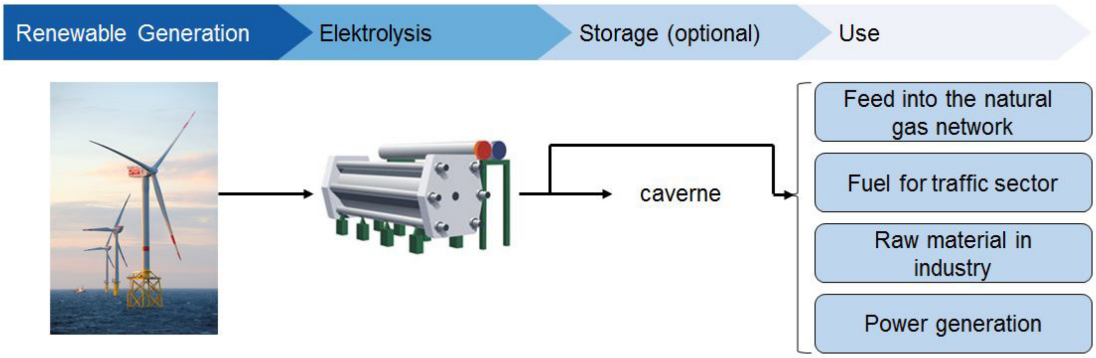

Fig. 6. Concept of wind-hydrogen [own illustration].

and comparatively low storage cost of 4-10 cent/kWh [11], they have a major drawback: there is only a limited expansion capability, because pumped storage power stations put topographical certain prerequisites ahead. The potential in Germany is nearly exhausted. In addition, the economic conditions for pumped storage power plants have deteriorated in recent years. The market revenue is highly dependent on the spread of maximum to minimum day-ahead price. However, this difference tends to be decrease under the current market regime. Combined with high effective network tariff burden, this means profits falling.

5.2. Hydrogen

Hydrogen, although being produced largely using natural gas, can also be produced by electrolysis of water. The production of hydrogen provides the ability to convert electrical energy into chemical energy. This hydrogen can be compressed and stored in caverns and can be converted back using fuel cells, turbines or gas engines. (Fig. 6).

The existing natural gas network offers a cost efficient way to distribute and store hydrogen. Currently the natural gas grid can take up to 5 % of hydrogen in its composition without any technical changes. With an energy capacity of 1,000 TWh [12] the natural gas network provides an enormous storage capacity. It must not be forgotten, that in the case of a decentralized hydrogen supply, large enough facilities must be available on site. However, local consumers of natural gas require a low-hydrogen composition. Another application of hydrogen can be found in the transport sector where it can be used as fuel in a fuel cell vehicle, where high efficiencies of the electric motor plus the lack of harmful local emissions are an important step towards a greener motorized mobility. Hydrogen is also used for many industrial processes, such as the production of ammonia-based fertilizers, in metal processing or in the hydrogenation of oils and fats.

Rather than using normal grid electricity for this energy conversion, a lossy process if the electricity could have been used elsewhere, the energy source for the electrolysis can be excess electricity. Wind-hydrogen concepts produce hydrogen downstream and deliver electricity upstream in times of demand. When using decentralised CHP units, there is also heat as a by-product, supplying residential areas or industrial estates. A working proof of concept is Europe's largest hydrogen filling station in Hamburg-HafenCity. The hydrogen station is not only used for the refueling of hydrogen buses and cars, but is at the same time an electrolyser producing hydrogen itself. Other concepts include wind-hybrid-power plants, which directly couple electricity and hydrogen production. The combination of wind turbines, CHP and hydrogen electrolyser not only shows that wind energy can be used as base load energy generation, but also that excess energy can be utilized and traded in the form of hydrogen

5.3. Batteries

Since February 2013, a Hamburg-based consortium led by Vattenfall Europe AG uses a heat storage battery to provide primary control in the network of 50Hertz Transmission GmbH. The 2 MW system consists of 1,600 lithium iron phosphate batteries with 400 Ah and is integrated into the Virtual Power Plant of the local utility. The batteries are housed in two 20-foot containers and are operated by control and power electronics, which is stored in two additional 20-foot containers.

In future, more stationary battery storage should be operated: batteries in conjunction with PV systems to increase own consumption, batteries coupled with charging infrastructure for electric vehicles in order to avoid network back draw in fast-charge and batteries for the operation of a stand-alone grid with renewable energy production. In addition batteries from other applications are reviewed to utilize a second application for e.g. electric vehicles or PV systems. The batteries could be aggregated with many other battery systems and are offered at the control power market. Thus, a reclaim of the facilities and economical operation can be achieved.

6. Regulatory framework and market incentives

The regulation determines to a large extent the economic environment of renewable energy. Regulation is a result of state intervention, which usually reorganizes the income and expenditure flows in markets with appropriate bonus or malus incentives. In the context of the energy transition the goal is to achieve preferred political effects on energy markets. Different regulatory instruments, such as the EEG on the power generation side or the Incentive Regulation (ARegV) in the grid segment, constitute these interventions and provide the regulatory framework of the energy transition. In its development an increase in regulatory intervention is observed. So far coordination between regulation objectives of the energy policy and energy-economic contexts cannot be sufficiently recognized. Needful is a superior approach, which tries to monitor the interactions of funding and regulatory elements at different stages of the value chain. The current discussions revolve around a new market design, to ensure the necessary investment incentives for the energy system in the future. Elements in the context of these considerations are grid usage, capacity premiums, load profiles, storage incentives or redesigning the EEG. In consequence an increasingly complex regulation tends to remain. The guiding can be to combine existing rules into existing and future business models. Further funding of demonstration projects is desirable in the medium to long term to ensure the necessary development of new technologies.

7. Recommendations and Outlook

The paper shows that in order to integrate increasing amounts of volatile electricity generation from wind and sun, major technical and economic challenges have to be mastered. One of the countries that have to face this challenge in particular is Germany, as it already has Europes largest share of renewables in the electricity grid. Actions underway are the further expansion of the grid and the development of appropriate technical measures on the supply and the demand side.

While grid expansion is an expensive and politically difficult task with growing opposition in the public when it comes to the actual implementation (”not in my backyard” attitude), flexible production of conventional power plants might be an easy and readily available measurement. However, technical limitations (must-run capacities etc.) limit the contribution of it to the grid problems. In addition, the current market design does not cater for the financial consequences of a voluntary reduction of the capacity factor of a plant. What is needed are changes in the market design and an accordingly adapted regulatory framework to continue to attract necessary investments in the energy sector.

The same goes for innovative energy storage concepts. At the moment, the only storage capacities are the traditional ones, like pumped hydro. Their available quantity, unfortunately, only reflects the need for balancing power ”in the old world” of energy distribution. It certainly will not be enough to replace a week-long wind calm or cloudy weather without sunshine for several weeks. New concepts like hydrogen storage could fulfil the need for long-term, large-scale energy storage, but again, can only be operated in a political environment which acknowledges the provision of storage and thus energy security in a way that allows for viable business models.

Another means to integrate fluctuating renewables and combine these with decentralised power generation are Smart Grid/Smart Market applications. The ubiquity of the internet combined with new or retrofitted appliances allows for a regulation of supply and demand in real-time and according to market rules. Moreover, it could help to keep decentralized energy at lower levels of the grid, e.g. by promoting the own consumption at the point of production - freeing transmission capacities of the nationwide electricity system and the associated regulation systems.

To put it in a nutshell, the challenges lying ahead for a secure and environmental friendly energy provision are large and profound. They require technical, but more over regulatory adjustments and innovations which are partly not fully understood today. This calls for continued R&D, but also the necessary support schemes for those market players that are willing to break new grounds in their own initiatives.

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