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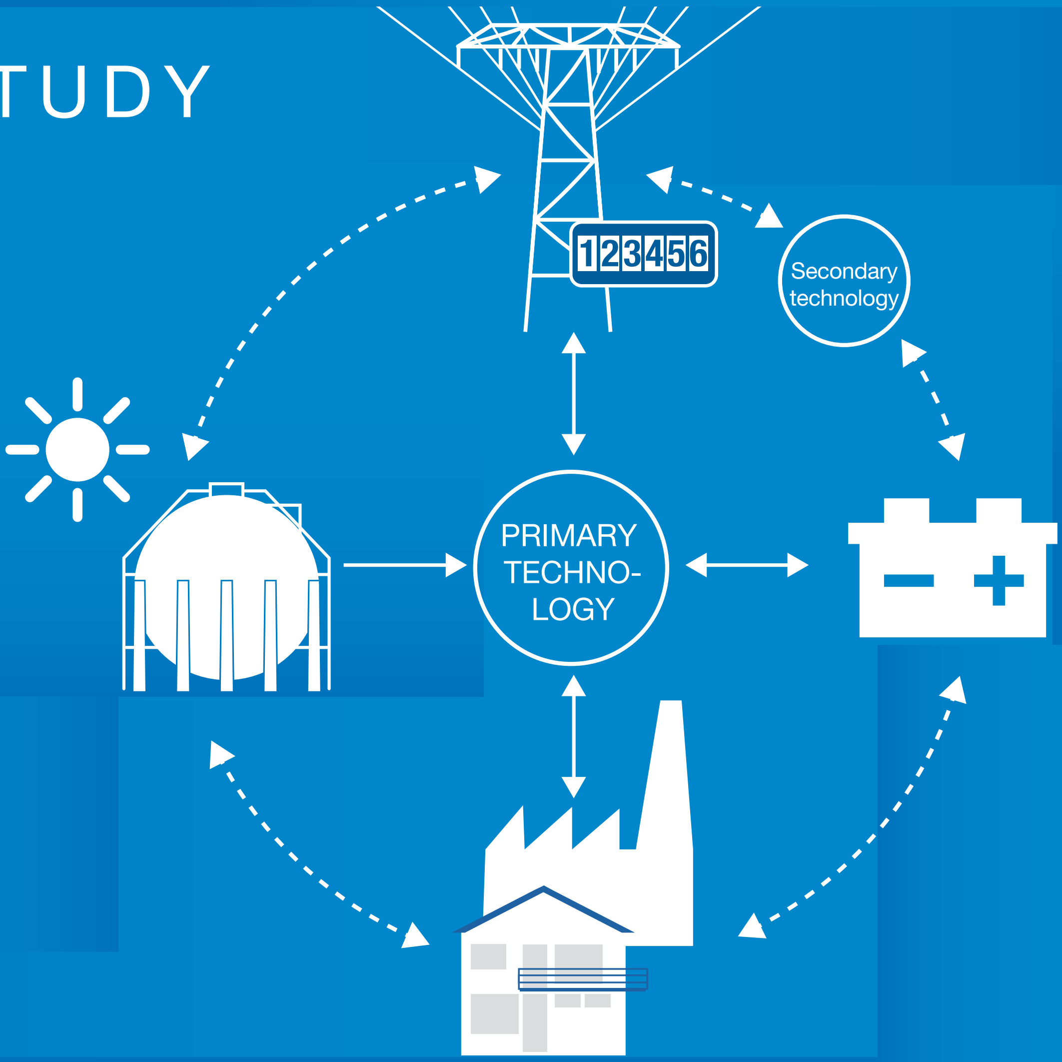

THE CELLULAR APPROACH

The basis of successful, cross-regional energy transition

ETG

VDE

Title

The cellular approach - The basis of successful, cross-regional energy transition

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Preface

Reflecting the ETG's position as a neutral, power engineering-based institution, its studies contain the findings commonly agreed upon by the members of the task force / the technical society. The joint results are arrived at following a constructive dialogue between frequently diverse positions. The studies do not therefore necessarily reflect the opinions of the companies and institutions which are represented through the involvement of their employees.

Foreword

The energy concept of the Federal German Government was adopted on September 28, 2010 [1]. This date is generally considered to signal the start of the "German energy transition", although the wheels had already been set in motion in 1990 with the Electricity Feed-in Act and in 2000 with the Renewable Energies Act. Five months later, immediately after the nuclear accident in Fukushima on 11 March 2011, further far-reaching decisions were taken with regard to the phase-out of nuclear energy. The time horizon of the objectives up to the year 2050 shows the consequences of the change in energy policy.

The most important cornerstones of the energy transition:

- 80 to 95% reduction of greenhouse gases (reference year: 1990)
- 50% reduction of primary energy consumption (reference year: 2008)
- 25% reduction of electrical energy consumption (reference year: 2008)

And by 2050 renewable energy sources should account for

- 60% of total energy consumption, and
- 80% of power generation

The last objective in particular represents a major challenge to the electricity sector. The present infrastructure, the principles of operational management and, not least, the existing market structures and the regulatory framework need to be completely re-assessed. The electricity industry is thus facing the biggest changes in its 150-year history. We can assume that the existing knowledge and the decades of experience will need to be fundamentally reoriented to achieve the ambitious energy transition goals.

If we consider the development of electric power supply from its inception at the end of the nineteenth century up to the present day, it is apparent that there is a desire, at least in some aspects, to return to the structures of the early days. This applies, for example, to the use of small, local generation plants, for which the network structure must be adapted. It will also be necessary to find new solutions for the use of DC or AC voltage for the transmission and distribution of electricity, given the increasing number of direct current loads, e.g. for lighting purposes, ICT and consumer electronics. But capacity balancing through storage and load shifting represents a major energy transition challenge. A significant increase in cross-regional energy balancing is made necessary by the unequal distribution of renewable energy potential, and storage is necessitated by fluctuating supply levels.

A further aspect is the advanced technologies which exist today, but which were not available when the energy supply grid was being established more than 100 years ago. Power electronics and broadband communications are key factors here. Technological advances have given rise to further developments in energy storage systems and energy converters. Different energy sources are now networked together in modern and sustainable energy supply systems to provide optimum technical and economical solutions for applications such as mobility, process heating, space heating, cooling, drives and ICT. Which raises the question:

What kind of modern energy supply system would we create if we could completely redesign the structure to reflect the new requirements and include these pioneering technologies?

To answer this question, the Task Force compiled a list of possible technologies for energy conversion and energy storage. It also created a universal energy scenario for Germany which includes both the provision of renewable energy as well as changing demand levels. Local supply forms the basis of the approach considered. This is referred to as the cellular approach. If it is possible to balance local generation and consumption at the lowest viable level in cellular structures in the future, this will yield significant opportunities for meeting the specific needs of renewable energy sources.

The social demand for a high security of supply, especially for energy-intensive industries, large conurbations and cities, often cannot be met at all times at the regional level. This requires more intensive energy transmission and extensive energy storage.

Electricity can only be stored to a limited extent, which is why alternative storage options for large amounts of energy are also considered. Gas[1] yields many advantages, especially with regard to storage. Therefore, it should be considered what role gas can play in a future energy system.

The Task Force reviews cellular and local concepts but also the consequences for power transmission if cellular networks are implemented. The required transmission structure is defined for an assumed expansion of decentralized renewable energy sources.

The ETG Task Force therefore examines some of these future challenges as the basis for discussion.

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[1] In this study "gas" covers natural gas, methane and hydrogen, and also mixtures of these. Other similar fuels, such as propane, are used nowadays in certain applications, however, the authors believe that such substances will not play a primary role in general power supply.

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1 Introduction

1.1 Objectives

The Task Force examines and describes concepts for a sustainable energy supply which go beyond short-term or medium-term planning. The concepts are based on the example of Germany.

The objective of the Task Force:

The power supply system of the future will rely more strongly on renewable energy sources and must increasingly take into account aspects of environmental compatibility. To achieve this, the viability of using new technologies also needs to be assessed in particular - where they are ready for use or are currently in development. Social acceptance, the impact on the economy and the security of supply must be considered in equal measure.

In contrast to other studies and development concepts, no attempt is made here to improve the existing energy system's ability to cope with future tasks through expansion and development. The aim instead is to meet foreseeable energy demand by creating a new energy system. This system will be based on known technologies and take the potential for development into account. There must also be stronger networking among the different energy sources.

The aim of this approach is to open the way for new energy supply concepts.

1.2 Structure of the study

There is currently no structure for an energy supply which is largely based on renewable sources, nor is there an ideal path for development. Numerous studies and investigations (e.g. [2], [3], [4]) have been undertaken aimed at determining possible future supply structures established by different stakeholders at different power supply levels, and to derive possible development paths based on these.

Methodologically, these concepts for finding potential future energy supply systems are often based on demand assumptions and assumptions regarding future generation from renewable fuels. The assumption values are very imprecise in both areas and have large ranges of variation, as they are strongly influenced by political and social exigencies. The necessary expansion steps are then determined based on these with the aim of developing the existing energy supply structure and of adapting it to anticipated future demand and renewables-based generation. This method does not adequately take into account fundamentally new energy supply structures and the integration of innovative conversion and storage technologies.

The method adopted by this Task Force differs from that of previous studies in that it develops and compares possible energy supply concepts (based on the example of Germany) without taking existing structures into account.

Starting points for the investigations are technology profiles for energy converters and energy storage units which reflect the present state of engineering knowledge and which estimate future innovation potential. The Task Force is aware that new discoveries (and resulting technical leaps) in the fields of physics, chemistry, biology or geology can throw the results of this study into a different light.

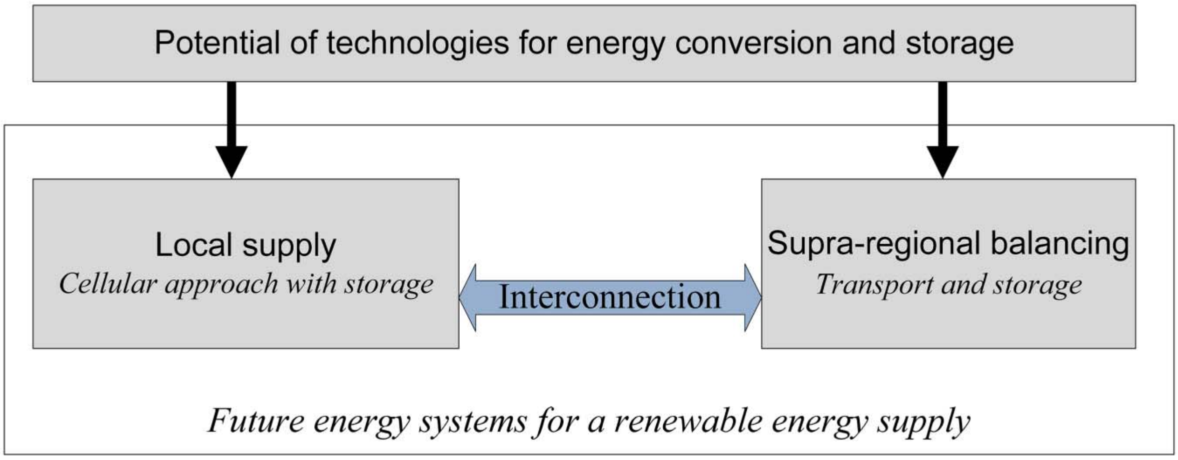

Figure 1: Methodology of the VDE Study "The cellular approach - The basis of successful, cross-regional energy transition"

The concepts are based on the prospects for renewable energy provision as well as the assessment and assumptions about future energy demand drawn up on the basis of a universal energy scenario for Germany. There is growth potential in onshore and offshore wind plants and photovoltaic systems. Hydroelectric and biomass power plants, however, are still regarded as an important part of the energy mix. Nuclear fusion is not considered in this study because although a technological breakthrough in nuclear fusion will revolutionize the energy systems, this is currently not in sight.

In terms of energy requirement, the multi-utility interconnection of electricity, thermal energy and mobility is gaining in importance. Current electricity demand levels can be reduced by improving efficiency. However, the increasing use of electric vehicles, heat pumps and air conditioning is raising the overall demand for electricity.

The central question which is addressed is:

Assuming there was an area with no existing energy system, how would you structure a modern supply system, and which technologies would you use to create a sustainable energy supply based primarily on renewable energy sources?

International terms such as "greenfield planning" or "greenfield design of future networks" (cf. e.g. [5], [6]) are already becoming common.

The VDE study "The cellular approach - The basis of successful, cross-regional energy transition" shows that decentralized structures need to be created and also that energy will need to be balanced supra-regionally in a future energy supply structure. These results underscore the fact that a local supply is possible in some cases (cellular approach), but that supra-regional structures will also be required: this study provides a basis for discussing these aspects.

Existing technologies for energy conversion and storage, as well as foreseeable technological developments are included here. Economic aspects and political incentives are not the focus of this study.

Recommendations for action are given with regard to research funding for technology development and the further development of economic and regulatory conditions.
The concepts proposed in this study are also assessed in terms of their feasibility.

2 Potential of energy conversion and storage technologies

2.1 Definition of the balancing group

An important basis for considering energy supply scenarios is the definition of balancing groups.

Energy can be brought from outside into a balancing group and removed from it in the form of "use". "Losses" are also incurred; this is the energy that is lost during conversion or transmission (usually as waste heat) and is then not available for commercial application within the balancing group.

For the purposes of this study, electricity, heat and gas are defined as the energy sources in the balancing group. Electricity is fed into the balancing group by power stations; primary energy is required for this. Fossil fuels, biomass, or nuclear energy, for example, are converted into electricity in thermal power plants. Other power plants such as wind, photovoltaic or hydroelectric power plants generate electricity from other forms of primary energy known as environmental energy because of their renewable nature. Thermal energy can be provided by power plants or be produced for different applications directly from primary energy sources (e.g. fuels), or from electricity. Gas plays a special role here. Energy in the form of gas can be introduced into the balancing group from outside (e.g. as a fossil energy source from a bore hole or from biomass), however it can also be generated by converting electricity (electrolysis or "Power2Gas"). In the latter case, no energy is fed into or extracted from the balancing group - there is simply conversion within it. Gas can thus be converted into electricity or thermal energy inside the group.

The main users of energy are households, industry, commerce and transport. These remove energy in the form of electricity, thermal energy and gas from the balancing group, and transform it into usable energy[2], for example for chemical processes, process heating, space heating, ICT or mechanical energy.

Storage facilities are used within the balancing group. They absorb energy (e.g. electricity) and release it again after the storage period.

Figure 2 below is a schematic representation of the balancing group and the different forms of energy. The main purpose here is not to offer an exhaustive description of the subject, but to provide a clearer understanding of the approach on which this study is based.

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[2] Useful energy is not a term with a standard definition, cf. energy forms in the glossary (p. 71)

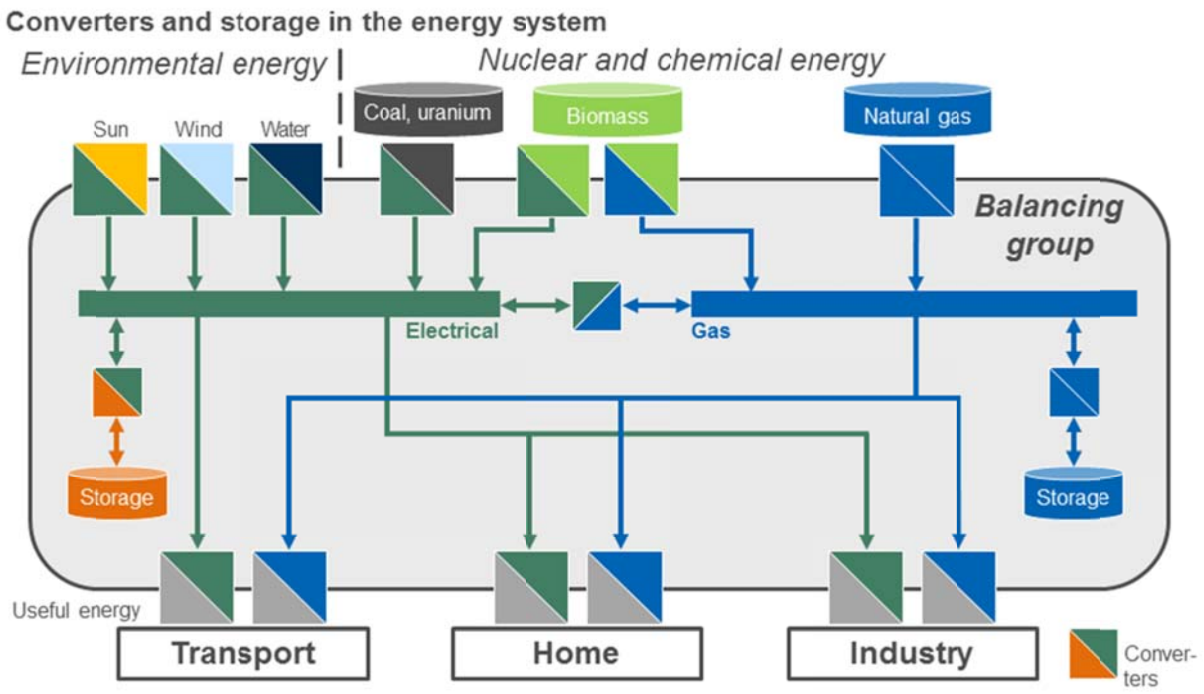

Figure 2: Energy sources with balancing group and interconnections

With regard to Figure 2, it should be added that, for the purposes of this study, a household fuel cell is classified as a thermal power plant, even though it has a very low output and is therefore not usually referred to as a power plant in general parlance. The interconnections shown have no direct importance in terms of networks, they merely show that a certain form of energy is used. It is initially of no matter whether energy is used locally or passed on to other consumers via cables.

For a future energy supply it is especially important to know the extent to which today's common energy sources, especially fossil fuels, can be replaced by electricity, heat and gas in order to supply consumers. Figure 2 shows that there is no application which could not be supplied by electricity or gas. This means that power could be supplied entirely from renewable energy sources without nuclear power and fossil fuels.

2.2 Content and structure of the technology profiles

Technology profiles serve as the basis for assessing the various energy options. For the purpose of this study, these profiles contain the underlying data for the different conversion and storage technologies, but not for energy transmission. The starting point for the profiles is the current state-of-the-art, including an assessment of the development potential. Innovative breakthroughs, such as the application of new physical phenomena, are not included in this list, since they are not predictable.

There are 28 technology profiles based on the classes of energy converter or energy storage. This underlines the new perspective of the energy system, which moves away from traditional generators and consumers. Within the classes the technologies are divided into types and their variants. Where appropriate, some variants are collected together to form a type.

The main features are the form of the delivered and the target energy, although technically exploitable losses, mostly in the form of heat, are also known as target energy. The level of efficiency achievable both today and in the future, and also the performance variables (in the case of storage, also the storage size) complete the technical characteristics. Where appropriate, the individual efficiency levels of different system components are also given.

The technology profiles include investment costs and an estimation of future costs. Current data are based on literature analyses, future costs on the players' own assumptions. The operating costs, especially those of converters which use fossil fuels, are dependent upon commodity prices and their fluctuations. In addition, the political and regulatory requirements of these converters have a large impact on the costs (e.g. taxes, emissions trading) and are therefore unspecified. Furthermore, estimates were made for acceptance risks associated with the technologies and CO_2 emissions into the atmosphere during operation.

Statements regarding the special features of the technology, including any necessary further development, trends and research requirements, are given in the remarks section.

2.2.1 Energy converters

The term converter is used in a general sense. Converters are technologies which supply energy to the balancing group, which convert energy into another form of energy within the balancing group or which extract energy from the balancing group. Energy-supplying converters can e.g. provide energy from "environmental energy" (kinetic energy from wind or water, electromagnetic radiation from the Sun), fossil fuels or nuclear energy to the balancing group. Conditioning converters convert one form of energy into another (e.g. electrolysers convert electricity into hydrogen). Energy-extracting converters remove energy from the balancing group to cover demand. Heat pumps are an example of this. All electric household appliances are therefore converters, but they are not listed here. Sometimes mixed forms occur, when for example heat losses from conditioning converters are exploited. Table 1 shows 17 converters classified into energy-supplying converters, energy conditioning converters and energy-extracting converters plus their development potential.

The other parameters are shown in Annex 1.

Table 1: Converters and their development potential

Converter type	**Development potential**		
	Low	Medium	High
Energy-supplying converters	Onshore wind plants, Solar thermal energy, Hydro power plants, Thermal power plants	Offshore wind plants, Photovoltaic systems, Geothermal systems	Small wind plants
Energy-conditioning converters		Micro CHP	Fuel cell *Power2Gas:* Ammonia production, Electrolysis, Methanation
Energy-extracting converters	Gas boilers, Thermal storage heating, Infrared heating	Heat pumps	

In addition to the converters that convert one form of energy into another, there are also converters that change only the magnitude of a form of energy, for example for the transmission of power over long distances. These converters are mentioned only in passing here because the exact form of these systems is not part of the scope of this study. The converters include, for example, transformers or power electronics for the electrical system, or compressors for the gas supply. For the transmission of energy such equipment also requires corresponding lines (cables, overhead lines, pipelines) in which more losses occur. The individual losses and the technical complexity of the different methods[3] are not quantified in this study; there are too many design possibilities.

2.2.2 Energy storage

The descriptions of the storage technologies focus mainly on the storage media themselves. The charging and discharging converters are included in the profiles if they are assigned exclusively to the storage unit. A general classification of storage systems into short term and long-term storage units, including the applications, technical features, self-discharge, possible cycles and examples, is given in Table 2. Short-term storage systems are further divided into power storage and load shift storage.

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[3] For example, in the power grid there are different operating frequencies (AC, DC), voltage levels, network topologies, ...

Power storage systems play a subordinate role in this study, since they are used in today's electricity power grid for control power and system services or in applications such as vehicles for saving energy (for example, regenerative braking).

Table 2: Classification of storage facilities by property based on [7]

	Short-term storage		**Long-term storage**
	Power storage	*Load shift storage*	*Seasonal storage*
Period	ms … min	min … h … d	d … Weeks
Application	Control power System service	Balance within one day	Long-term slack Seasonal differences
Technical features	High power to storage capacity ratio	Low charge and discharge losses	Very large storage capacity
Self-discharge	High	Low	Very low
Cycles	Many per day	Few per day	Few per year
Examples	Flywheel storage units Capacitors Batteries	Batteries Compressed air storage Pumped storage power plants	Chemical storage plants (hydrogen/methane)

Load shift storage plants balance the energy during one day. Low-level self-discharging is allowed, although charging and discharging losses should be kept to a minimum. The load shift storage plants have few cycles per day. The long-term storage facilities, also referred to as seasonal storage facilities, must compensate for long-term slack and seasonal differences in energy supply and energy consumption. Very low self-discharge rates are therefore significant.

Many of the storage facilities listed in the technology profiles in Annex 1 have electricity as their delivered and target energy. The energy form of the storage facility itself is however generally different[4], for example, chemical energy in batteries, potential energy in pumped storage power plants or rotational or kinetic energy in flywheels.

The efficiency levels η of these storage facilities are between 70 and 95%. However, the self-discharge rates also need to be evaluated. The self-discharge rate is a percentage of the total storage capacity per unit of time and describes the loss of usable energy. In flywheel storage systems, for example, friction losses are so large that the self-discharge rate reaches 5% to 15% of the stored energy per hour. In double layer capacitors, leakage currents cause self-discharge rates of 10% to 20% per day. In batteries, the self-discharge rate is very low by comparison, accounting for just a few per cent per month. However, self-discharge in batteries is highly temperature de-

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[4] Therefore, appropriate converters are generally upstream and downstream of the storage units.

pendent. High temperatures in particular cause a significant increase in self-discharge.

Gas storage systems represent a further major energy storage technology. No further conversion takes place in them, rather the gas is stored as an energy source with the respective energy content. This is the main difference to electricity, which cannot be stored directly in large quantities. An important parameter, the energy density, is not the property of the gas storage unit, but of the gas itself. Table 3 shows the energy densities of hydrogen and natural gas in relation to their volume or mass. The energy densities for hydrogen are also broken down for different pressures. The characteristic values for petrol are given as reference. In terms of its mass, hydrogen has the highest energy density, however the energy density is low in relation to the volume.

Table 3: Energy densities by volume and mass for hydrogen, natural gas and petrol [8]

		related to volume	related to mass
Hydrogen	(liquid)	2,360 kWh/m³	33.3 kWh/kg
	(70 MPa)	1,855 kWh/m³	
	(20 MPa)	530 kWh/m³	
	(atmospheric pressure)	3 kWh/m³	
Natural gas	(20 MPa)	2,580 kWh/m³	13.9 kWh/kg
Petrol		8,760 kWh/m³	12.7 kWh/kg

The energy densities of gases are very high in comparison to other storage methods. Lead-acid batteries achieve an energy density of only 100 kWh/m³, and lithium-ion batteries of 200 kWh/m³. In compressed air and pump reservoirs the energy density is very low at about 1 kWh/m^3.

Gas storage has a high efficiency of over 99% and self-discharge is negligible. The service life is also very high.

Heat storage systems round off the storage possibilities. They are installed in decentralized form close to the demand, since heat is not viable as an energy source for balancing supra-regional energy.

2.3 Interim result

Convergence of energy sources

The technological developments in the field of energy converters and energy storage permit greater convergence between the energy sources. Firstly, there is a wide range of technologies that enable application-specific application. This makes it possible to optimize the respective advantages of the energy sources for energy supply, transmission, distribution, storage and use. For example, temporal decoupling of the use of heat and electricity is made possible by thermal storage. This yields advantageous operating conditions for the overall system e.g. through fuel cells and heat pumps which can reduce peak loads in the electricity supply and thus reduce the demand for transmission. It also allows the overall efficiency of the power system to be raised.

Conclusion

Some of the listed converters and storage technologies have only shown their potential so far in the laboratory or in pilot plants. Safe, robust, easy-to-use and affordable products must be brought to market-readiness through additional research and development work.

3 Local supply - the cellular approach

3.1 The basic idea of the cellular approach

3.1.1 Introduction

A power supply which is to be based as far as possible on renewable sources requires significantly higher installed capacity due to the volatile generation characteristics. To compensate for the volatility, the consumption must adapt to the feed; (seasonal) storage is also required. Today's energy networks also need to be restructured. For this reason, the principles on which the network planning and operation are currently based must be rethought. The study investigates whether e.g. a cellular approach can be adopted for the future planning and operation of energy systems.

3.1.2 The principles behind today's networks

A number of principles are listed below which are essential for the design and operation of the existing electrical and gas networks.

Compliance with the mains frequency of 50 Hz

A significant objective of the operational management of electrical networks is maintaining a stable frequency of 50 Hz within narrow limits. Any deviations which occur are due to load variations which are compensated by the control power supplied by the relevant plants. Downward frequency adjustments indicate undergeneration, upward frequency adjustment indicate overgeneration. These frequency deviations are used by the power plants to control power/frequency.

Narrow limits for voltage stability

At all voltage levels, from high and extra-high voltage to low voltage, efforts are made to maintain the respective nominal voltage within narrow limits. All equipment must work within the specified limits without any functional impairment. Surges in particular can lead to the destruction or at least reduced service life of installations and equipment; undervoltage may cause reduced functionality.

Maintenance of voltage quality

Voltage quality is the conformity of nominal mains voltage values with the actual quantities. These include frequency and voltage level as described above and also the shape of the curve and thus the harmonics, as well as possible errors. A prime example of a temporary disturbance is flicker which occurs during short interruptions for resolution of atmospheric interference or cyclical load changes.

Continuous use of AC voltage

At the beginning of electrification there was much heated discussion about the use of DC or AC voltage, however the consistent use of AC prevailed with time.

Supply reliability from interconnected networks

The electric networks were constructed on the assumption that sufficient numbers of power plants were available for generating electricity, and that they were located as close as possible to the load areas and could be used as required. These are the cornerstones of today's supply reliability, in conjunction with the interconnection of the integrated and distribution networks. This is helped, among other things, by the (n-1) planning and operating criterion.
Disregarding critical applications such as hospitals, data centres or traffic control centres, which all have their own emergency power supply, Germany enjoys a very high level of supply reliability to consumers today, internationally speaking.

Network stability through ready reserve

Networks with predominantly fossil-fired and nuclear power plants have large rotating masses in the form of connected turbine/generator units. These make a major contribution to the short-term stability of the networks. Generation facilities which are connected to the networks via power electronics have different properties and only contribute to a limited extent to grid stability.

Unidirectional operation of gas networks

Gas networks are designed for one-way flow today. The return feed to higher-pressure networks is only planned in exceptional cases, e.g. in larger biogas feed facilities.

Uniform quality parameters for gas

Volumetric gas billing requires consistent quality parameters such as specific energy content but also combustion parameters such as the Wobbe index in larger contiguous network areas. Potential levels of flexibility yielded by modern measuring and simulation processes and flexible equipment are not yet being exploited. Thus, the potential benefits deriving from the simultaneous transmission of different fuel gases e.g. through higher proportions of hydrogen in natural gas cannot be used.

In conclusion, it can be said that all the principles described are of significance. These were further refined over time and adapted to changing requirements. However, if they are compared with the technical options available today, new technologies now exist which have only been exploited to a limited extent so far in operational management and optimization. These include the widespread use of power electronics, which could alter the issue of frequency and voltage stability, broadband communications, as well as modern control and optimization methods such as neural networks.

3.1.3 New principles of network planning and network operation

Automation technology as a model

It is now generally acknowledged that the future of electric energy supply as a whole will become more decentralized and involve a larger number of smaller units. Today there are more than one million generation facilities in the Federal Republic of Germany which need to be integrated into existing networks still characterized by a high proportion of large generation units. The question arises of how the electrical energy supply system should be restructured if the proportion of decentralized (renewable) producers continues to rise.

Automation technology could serve as a model for this. In automation, there has been a massive shift in the last few decades towards intelligent decentralized units that are interlinked to operate in a system. Two principles have prevailed in the design and operation of such structures which will be helpful in the design of electrical networks of the future.

The first principle concerns the basic structure of automation systems. Current thinking is that the optimum structure has been achieved if the process to be controlled is recognized or reflected in the structure of the I&C.

The second principle concerns the hierarchical processing of data and information. Automation engineers have learned to perform processing at the lowest level. If processing is shifted to a higher level, this can quickly lead to capacity bottlenecks or delays.

Thus the question arises of how the energy system of the future should be structured if it is to be designed based on the above principles.

The new rationale for the energy supply of the future

If the two principles for automation systems described in the previous section are accepted, and they are applied to energy systems of the future, this means

Balancing energy generation and consumption
at the lowest possible level.

This principle is often used already to describe so-called microgrids [9] working in stand-alone operation. This, however, is a different context which will not be explored here.

3.1.4 The cellular approach

It is examined whether the principle of self-sufficient energy cells can be realized across all energy supply levels. This means that a number of cells in one level are represented again as a single cell at the next level up and are treated according to the same basic principle. It is therefore conceivable for the energy supply structure in Germany to be based around given local conditions and administrative levels such as: house, road, urban district, town, region, administrative region, and state. It is important to mention that the energy cells themselves follow a multi-modal approach, i.e. all types of energy such as electricity and heat used in the cells are considered.

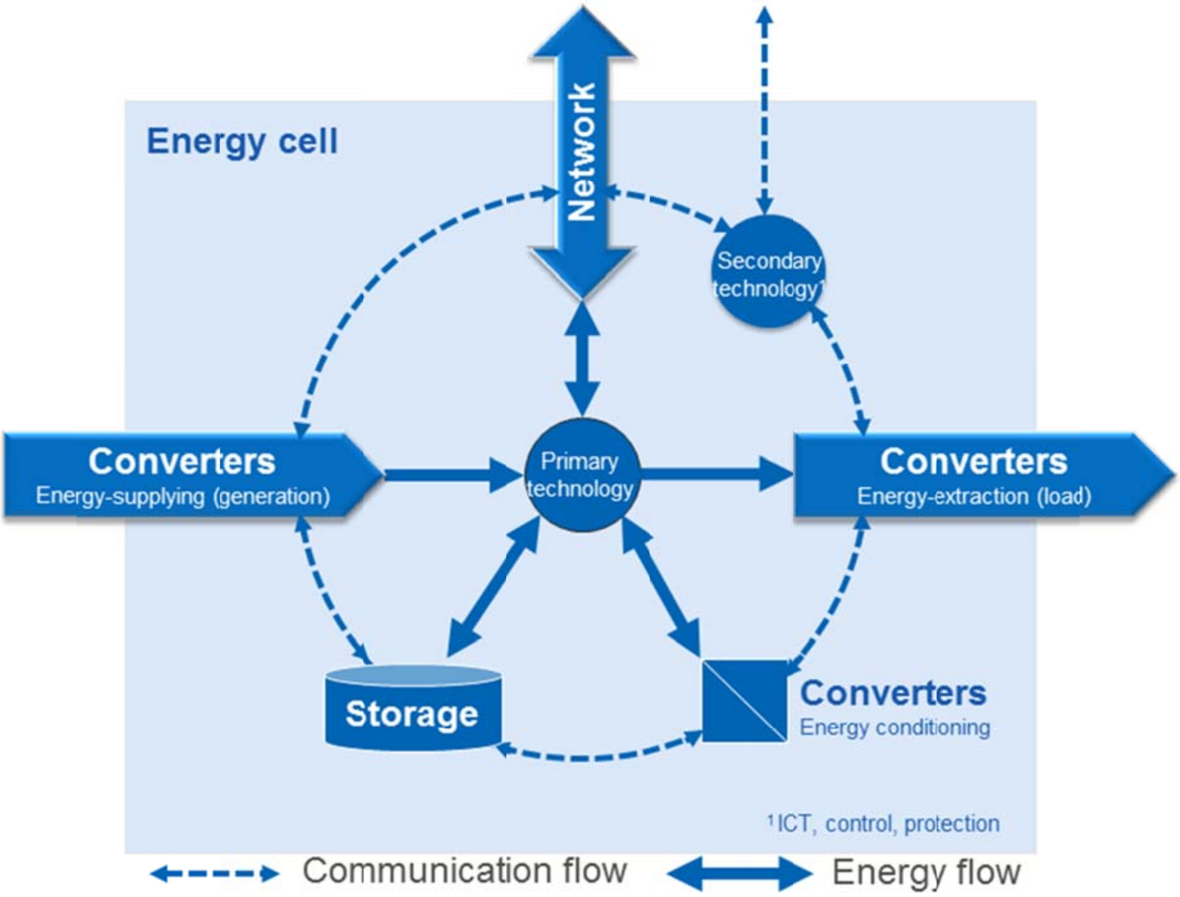

Figure 3: **Basic structure of an energy cell**

Figure 3 shows the basic structure of an energy cell. As a superset, each cell can have its own energy-supply converter (commonly referred to as generation units or generation), energy-extracting converters (loads) and one or more local storage units with different technologies. Conditioning converters also enable the conversion between energy forms within the balancing group.

A special unit is used for controlling and monitoring; this includes necessary protection functions. It is responsible both for the overall management of the existing facilities as well as the communication links to adjacent cells and the next level up. Subsets of facilities are possible. A conventional installation of a detached house would therefore include only the unit "load". Control and monitoring would be taken care of as in the past.

Externally the energy cell is represented by just a few parameters. In terms of load management, these could be performance values which are required or made available in the next time segment. Data confidentiality issues must be resolved conceptually.

The new rationale, i.e. balancing generation and consumption at the lowest possible level, can have a significant impact on the development or the enhancement of existing networks, It can also influence the construction of new plants in terms of the energy sources used.

General procedure

The Task Force uses a cellular approach in the form of green-field planning for the assessment of energy networks for local balancing of energy. Three typical types of energy cells are examined:

- Home
- Commercial-Retail-Services (CRS)
- Industry

In these three types of energy cells, energy demand and the possible provision of energy are shown in each case based on the energy form. Local energy supply concepts are also developed and evaluated. Generation and load levels over time have been factored in in simplified form.

The managers of the respective energy cells select relevant technologies to ensure a supply which is either self-sufficient or includes a connection to networks. Managers e.g. of the home energy cells are the house owners who opt for a suitable heating system, storage, etc. based on various criteria.

The cellular approach aims to balance energy demand with energy supply in the smallest possible units. The smallest unit of a home energy cell is thus a house. The energy cells provide energy themselves, e.g. in the form of wind plants or photovoltaic systems. Excess energy can be stored locally, but can also be used for other local energy cells via energy networks. Three scenarios are investigated for the local supply of the three types of energy cell:

- Energy cell with self-sufficient supply, without network connection
- Energy cell with electricity network connection
- Energy cell with gas network connection

For the purposes of this study, self-sufficient supply means a supply with no network connection; the overall balancing aspect of self-sufficiency is not examined. Figure 4 shows a variety of technologies from chapter 2 for the supply of energy cells. Each energy cell can take in energy in the form of heat, electricity, or gas, as is shown on the left. Demand, in the form of heat, mobility and electrical appliances such as ICT, lighting or mechanical applications, is indicated on the right. In the middle are various conversion and storage technologies.

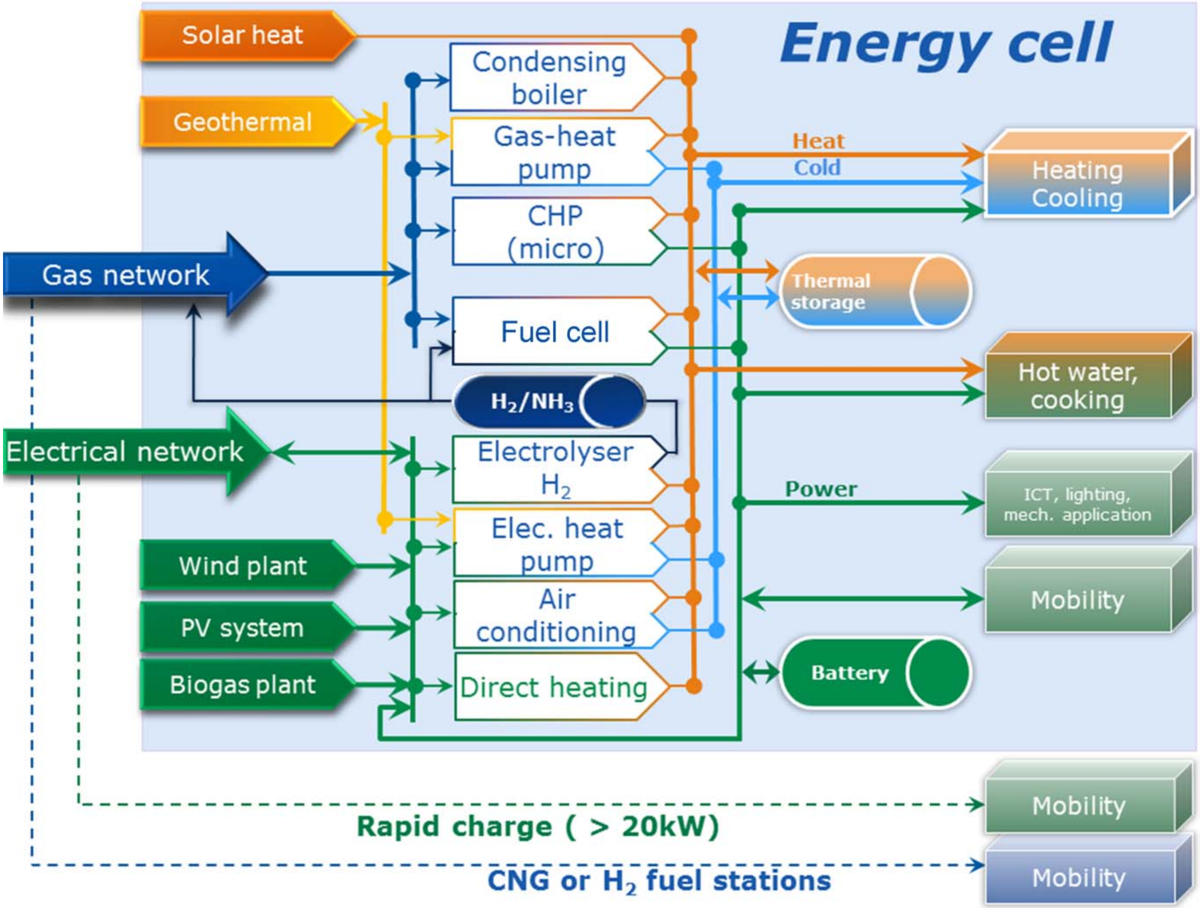

Figure 4: Technology portfolio for the cellular approach

The energy requirement for mobility can be met either internally or from fuel stations outside the energy cell.

It is assumed that all the technologies shown in Figure 4 are not used at the same location in a home or CRS energy cell. Different special variants will eventually prevail. In large Industry energy cells with different processes, by contrast, it is conceivable that a number of technologies will be used. However the needs of industry are very individual and therefore general statements are difficult to make.

3.2 Home energy cell

The energy requirement of households consists of electricity, heat and mobility. The demand for space heat is set to fall substantially over the next few decades. Significant reductions are also possible in electricity demand. The energy demand for mobility can become a new load in the home energy cell. This study provides no assessment of whether the mobility requirement will still be met largely by privately-owned cars, car sharing, or by public transport, bike or on foot. It is conceivable that electric cars will at least partially be powered by electricity from the home energy cell. Vehicles with internal combustion engines or fuel cells must, however, be refuelled at external service stations.

Table 4 shows the typical requirement for a home energy cell today and also the assumptions made in the study. There are considerable variations and the many factors affecting the energy demand make an assessment very difficult. The assumptions are based on the values given in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Table 4: Energy requirement of home energy cells

Requirement	Requirement today $E_{\mathrm{HH}\ 2013}$	Assumed requirement $E_{\mathrm{HH\ A}}$
Space heating	10,000 ... 30,000 kWh/a	2,000 ... 6,000 kWh/a
Hot water	3,000 ... 6,000 kWh/a	3,000 ... 6,000 kWh/a
Electricity	1,500 ... 6,000 kWh/a	1,000 ... 2,000 kWh/a
Mobility	5,000 ... 40,000 km/a	5,000 ... 20,000 km/a

The mobility requirement is given as distance travelled in a year. It is not possible to specify the amount of energy required without mentioning the corresponding energy source. For example, the energy requirement of an electric car is approx. 15 kWh/100 km. A modern diesel-engine car needs approx. 4 litres of diesel for this, yielding a requirement of 60 kWh/100 km.

Also the energy requirement is strongly dependent on the various technologies which are used in the home energy cell. For example, a condensing boiler needs more gas energy than a heat pump needs electric energy.

3.2.1 Self-sufficient home energy cell

The extensive investigations conducted in this study and presented in Annex 2 show that detached and terraced houses in particular can be run autonomously, i.e. without any network connection. However, it is not possible to achieve energy self-sufficiency for apartment blocks. The potential for renewable energy deployment is too low for this in these energy cells.
Achieving an autonomous supply requires a high degree of "over-dimensioning". Back-up systems are necessary to ensure a reliable supply. A network can serve as back-up in the event of technical equipment failures in the building, and can also absorb the excess energy.

3.2.2 Home energy cell with electricity network connection

In the next step, the connection of the home energy cell to the electrical grid is examined. The demands on the electrical grid may increase considerably compared to today: on the consumption side due to heat pumps and electric mobility, and on the generation side due to photovoltaic and wind plants. The relevant criteria are firstly the maximum capacity of a home energy cell and secondly the maximum combined capacity of multiple home energy cells. Simultaneous feed-in by generators and consumption by heat pumps and electric cars increases the simultaneity level significantly.

The simultaneity factor g is a measure of the extent to which all of the cells require or feed in electricity at the same time. In households with standard devices (except electric heaters and electric water heaters) the simultaneity factor g_{∞} is put at 0.1 to 0.2 today given simultaneity of a very large number of customers [10]. The simultaneity creates a situation in which, for example, 1000 home energy cells with a maximum capacity of $P_{\max 1}$ 10 kW do not need a total of 10,000 kW. With a simultaneity factor of 0.1 the sum of peak loads tends towards 1,000 kW, and towards 2,000 kW with a simultaneity factor of 0.2. Thus, the peak load proportion per household would be 1-2 kW for a very large number of customers $P_{\max 1}$ $(n \rightarrow \infty)$. It follows that the grid equipment can have smaller dimensioning.

For comparison, the first row of Table 5 lists today's standard design criteria for partial electrical supply. On the consumption side it can be seen that the peak load proportion for very many customers $P_{\max 1}$ $(n \rightarrow \infty)$ is significantly lower than the peak load $P_{\max 1}$ for home energy cells. During feed-in the simultaneity is very large, because photovoltaic systems, for example, all feed in at the same time, thereby neutralising the effect of load equalization.

In addition, two assumptions are made in order to highlight the trends for the requirements placed on the electrical networks by the home energy cell. The implementation and utilization of demand side management (DSM[5]) plays an important role here. In assumption 1, no DSM is assumed. On the consumption side, a significant increase in maximum power $P_{\max 1}$ is expected, caused by electric vehicles and heat pumps. This also raises the simultaneity and the peak load proportion. The result would be high demand for network expansion at the low voltage levels.

In assumption 2, by contrast, it is assumed that there is DSM which benefits the network. In addition, storage can significantly reduce peak loads on the consumption and feed-in sides. The values for the maximum power can be adjusted by the controller and merely have an exemplary character here. The peak load proportion can be significantly reduced by DSM.

Table 5: Home energy cell trend - Requirements for electrical networks

	Consumption		Feed-in	
Today	g_∞ $P_{\max 1}$ $P_{\max 1}$ $(n \rightarrow \infty)$	= 0.1…0.2 = (5 … 10)kW = (0.5 … 2)kW	g_∞ $P_{\max 1}$ $P_{\max 1}$ $(n \rightarrow \infty)$	= 0.8…1.0 = (1 … 30)kW = (0.8 … 30)kW
Assumption 1 (no DSM)	g_∞ $P_{\max 1}$ $P_{\max 1}$ $(n \rightarrow \infty)$	= 0.5…1.0 = (10 … 20)kW = (5 … 20)kW	g_∞ $P_{\max 1}$ $P_{\max 1}$ $(n \rightarrow \infty)$	= 0.8…1.0 = (1 … 30)kW = (0.8 … 30)kW
Assumption 2 (with DSM)	g_∞ $P_{\max 1}$ $P_{\max 1}$ $(n \rightarrow \infty)$	= 0.8…1.0 = (1 … 2)kW = (0.8 … 2)kW	g_∞ $P_{\max 1}$ $P_{\max 1}$ $(n \rightarrow \infty)$	= 0.8…1.0 = (1 … 2)kW = (0.8 … 2)kW

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[5] Process designed to influence the quantity or the consumption characteristics of the energy consumed simultaneously by the end consumers.

3.2.3 Home energy cell with gas network connection

The strain on the gas network will not change substantially. Until now, gas networks were dimensioned for supplying households, based on the heating requirement. It is expected that the demand for heating will be significantly reduced in the next few years. These reductions will scarcely be compensated by the expanded range of applications.

The simultaneity factor g_∞ in the gas network is already very large; a simultaneity level of 0.8 to 1.0 is expected because all households heat at the same time in the winter. There is no feed-in here.

The prospects for the home energy cell, based on assumption 1, indicate that the maximum required capacity will be reduced. This is summarized in Table 6. This means that future delivery requirements for the gas network will scarcely change in terms of capacity and energy. However, it is conceivable that gas networks will be capable of recovering energy in the future.

Gas networks with DSM were not investigated, as no DSM is required for these.

Table 6: Home energy cell trend - Requirements for gas networks

	Consumption		Feed-in	
Today	g_∞ $P_{\max 1}$ $P_{\max 1}$ ($n \to \infty$)	= 0.8…1.0 = (15 … 30)kW = (12 … 30)kW	*not provided*	
Assumption 1	g_∞ $P_{\max 1}$ $P_{\max 1}$ ($n \to \infty$)	= 0.5…1.0 = (5 … 15)kW = (2.5 … 15)kW	g_∞ $P_{\max 1}$ $P_{\max 1}$ ($n \to \infty$)	= 0.8…1.0 = (5 … 15)kW = (4 … 15)kW

3.2.4 Interim result for the home energy cell

The trend towards a cellular approach can already be seen today, in particular in the home energy cells. This is broadly characterized by self-supply from below.

Home energy cell with self-sufficient supply but no network connection

The cellular approach shows that an autonomous supply is possible, especially for detached houses. However, the overdimensioning and back-up requirements mean that autonomous supply does not appear to be viable for general application and is therefore not considered any further.
Home energy cells may in principle be connected to each other through electrical or gas networks.

It can be assumed that in the future a single network connection in the form of electricity or gas will be sufficient for most home energy cells.

Home energy cell with electricity network connection

The electrical networks are not designed for high load and feed-in peaks. To limit the maximum capacity which the electrical network would have to supply to or accept from the home energy cell, a combination of load shifting and energy storage would be useful. In addition, it must be ascertained whether it would make sense to replace the 230/400 V three-phase system with a higher voltage three-phase system or with a DC power system.

Home energy cell with gas network connection

Today's gas network will also be able to ensure adequate supply to the home energy cell in the future. Depending on the technology, the feed-in of energy to the home energy cell at the lowest level is basically possible and appears promising for the future. The flow of energy into higher pressure networks. involving larger amounts of energy, is at present only possible using compressors at the coupling points (gas pressure control systems). These are not currently available.
If a home energy cell is connected to a gas system, it is practicable to obtain the heat supply from combined heat and power. Reversible fuel cells, featuring a favourable combination of fuel cells and electrolysis operating in conjunction with a hydrogen storage system, appears particularly interesting for the future.

3.3 Commerce-Trade-Services energy cell

The trend towards a cellular approach would also appear to have significantly intensified for the CTS energy cell and that this is no longer reversible. Self-sufficiency is increasingly apparent in the individual sectors or businesses as a result of the rising cost-effectiveness of photovoltaic systems and cogeneration plants. On the basis of the energy requirement, the CTS energy cell requires in most cases a mains connection because in these cells insufficient energy can normally be "harvested" to permit balancing group autonomy or even energy self-sufficiency. To achieve supply reliability, an energy supply must therefore be provided from outside. The supply reliability requirements for the CTS energy cell are significantly higher than those for the home energy cell. For example, the CTS energy cell also includes supermarkets which at certain times have high requirements regarding the reliability of supply on account of the refrigeration equipment.

The network connection can either be to an electrical or a gas network; the calculations for this are shown in Annex 2.

In the investigations for the supply of the CTS energy cell it clearly emerged, however, that the demand of the individual CTS energy cells depends very much on their equipment and also on the type of cell. It is not therefore possible to make a blanket assumption for all CTS energy cells. It is also not possible to make a general statement on the interconnection of individual energy cells.

The examples below apply exclusively to the analysis of the energy cell of a supermarket.

3.3.1 Self-sufficient CTS energy cell

A self-sufficient supply structure is not generally possible in the CTS energy cell due to the small amount of space available for photovoltaic and wind systems, meaning that a connection to the electrical or gas network must always be available. Another alternative could be to establish links to the Industry or home energy cells. This, too, must be differentiated on a case-by-case basis, as the individual requirements and the resulting demand and surpluses differ in the various sectors. Future developments may make it possible for small service companies to have a self-sufficient supply.

3.3.2 CTS energy cell with electrical network connection

There is nothing fundamentally new about the CTS energy cell connection to electrical networks. The various concepts are described taking a supermarket as the example, however this can also be applied to other CTS sectors or adapted. However the specific needs of the individual CTS sectors need to be analysed in detail.

In addition to the connection to an electrical network, the CTS cell also has a renewable power supply from photovoltaic systems, however this will not be possible to meet all the cell's energy requirements due to lack of space. If the photovoltaic systems generate a high level of power which exceeds the cell's actual demand at certain times, it is possible to install storage in the form of batteries etc., or to feed the power into the electrical grid. It must be ensured, however, that this does not exceed any maximum limits for the electrical network.

The heat demand of the CTS energy cell can be met by direct heating. Theoretically a heat pump can be used, but this must be in the necessary performance class > 50 kW. It should also be possible to store any excess heat, thereby optimizing operation. The heat requirement is low compared to the electricity requirement of the supermarket in the example. In other CTS sectors, the heat requirement can significantly exceed that of electricity. It is therefore not possible to quote a specific figure.

In addition to providing heat, a further decisive role is that of providing refrigeration for cooling systems. A further energy demand in the future will arise from electric vehicles. Charging stations are planned for this, which in turn are supplied directly from the electricity network or from an existing photovoltaic system. Most of the charging stations are for employees. Charging stations for customers (of a supermarket in the example) are not included in the cell.

Overall, it is possible to effect demand side management (DSM) in a CTS energy cell with a connection to an electrical network. Load shift can be achieved through the use of storage. The large range of cooling facilities found in supermarkets can be used for this. In the event of a local energy surplus, it is possible to use the refrigerators for load shifting and thus as "storage", by cooling them to below the normal temperature. If supply bottlenecks arise due to network congestion or high consumption in the rest of the network, the refrigeration can be switched off for a period of several hours or even days (depending on the thermal insulation).

3.3.3 CTS energy cell with gas network connection

If there is only a gas connection, it should be borne in mind that an electrical energy supply is necessary for most applications in the CTS energy cell. For this reason, the conversion process from gas to electricity must be based on electrical demand. The problem with this approach, however, is that too much heat is often provided. This can only be passed on to the other networked energy cells and used there. A storage unit can absorb a temporary surplus of generated heat and release it as required, however there is no advantage if there is insufficient overall thermal demand.

Heat and electricity are supplied by converting the gas using micro CHPs or fuel cells. Fuel cells would appear to be more suitable for the requirements of the CTS energy cells than micro CHPs, as the ratio of electricity to heat is better suited to the usage profile.

Both micro CHPs and photovoltaic systems are factored into the gas connection in the investigations (see Annex 2). The storage of electrical energy is also required in this system to cover a very high proportion of energy demand by renewable energies.

Overall energy self-sufficiency is not possible here because it is not possible to supply the CTS energy cell due to the comparatively low proportion of renewable energy sources.

3.3.4 Interim result for the CTS energy cell

For the future energy supply of CTS energy cells, the trend is towards a cellular approach which is dominated to a large extent by self-supply from below. The result for the network operators is a complete restructuring of the planning principles based on a cellular supply. For this, a political-regulatory environment must be created and funding provided for the development of innovative supply concepts.

CTS energy cell with self-sufficient supply and no network connection

Self-sufficiency is not possible for the CTS energy cell examined here.

The energy needs cannot be met purely self-sufficiently because not enough energy is supplied from renewable energy sources. The power demand and the energy supply from renewable energy sources are not always the same, which makes it necessary to have return feed from the CTS energy cell in the higher-level grid at certain times if direct storage in the cell is not possible. The excess energy can thus be delivered to other CTS energy cells or also to home or Industry energy cells. From this perspective, coupling of the energy cells via a network is also useful, meaning that a network connection for the CTS energy cell is required in any case.

In particular in the service sector, self-sufficient energy cells are basically possible, similar to those in the home sector.

CTS energy cell with electrical network connection

CTS energy cells require a network connection in any case in order to meet their energy requirement in full. This can be effected via a modern medium voltage network connection or, depending on the configuration of the energy cell, via a modern low-voltage network connection. The aim is to connect the individual cells effectively with each other. As can be seen in Annex 2, the connected load will be above the present level.

The energy network planning needs to be coordinated with the zoning and development planning to make sure there are no conflicts. Storage must be provided in any case for load shifting, however the regulatory framework for storage needs to be adjusted.

CTS energy cell with gas network connection

Supplying the CTS energy cell via a gas connection is possible in principle and the current network technology is considered adequate for this task. Some adjustments are necessary to the building for this. This requires the further development of energy converters in order to achieve higher efficiency in the conversion into electrical energy. This is largely dependent upon which developments the manufacturers have in the pipeline at the relevant time (can be influenced by government support) and how these can be deployed for the particular cell. The gas network could in principle absorb any necessary return feed.

3.4 Industry energy cell

Industrial enterprises come in a variety of different forms and manifestations, and thus have very different demand characteristics. The precise forms of energy and respective demand levels depend on the type of products and manufacturing processes. Just as with the CTS cell, it is also impossible to assume a single supply scenario for the industry energy cell. This is shown in section 4.4.1. Therefore, only typical examples of different sized energy cells are considered in this chapter. These are:

- small industrial companies
- industrial areas and
- industrial parks

Characteristic parameters are given for each of these energy cells, and different energy consumption properties, future energy generation methods and storage forms and typical load profiles are also examined. Companies' future requirements are also described and a possible future concept outlined.

As the size of the energy cell increases (resulting in a higher energy supply intensity), it becomes increasingly dependent on the supply of energy from outside the cell and the demand cannot be met locally.

3.4.1 Total energy requirement of industry

The following information on industry's energy requirement and supply is based on a study by AG Energiebilanzen e.V. (AGEB) for the Federal Ministry for Economics and Technology from the year 2013 [11]. The graphical representations can be found in Annex 2.

Final energy consumption of industry

The final energy consumption of industry amounted to 722TWh in 2012. This represented roughly 29% of the total final energy consumption in Germany. Industry therefore tops the list, followed closely by transport (including rail, road and air transport as well as coastal and inland waterway shipping) at 28%. Then come home at 27%, and finally the Commerce, Trade and Services sector (CTS) at 16%.

The final energy consumption of industry is characterized mainly by the production processes of the individual sectors and companies. The energy consumption levels for air conditioning, lighting, information and communication technology (ICT), space heating and hot water are, however, related to buildings and employment. They differ very little between different branches of industry.

In 2012 approximately 70% of industrial final energy consumption was accounted for, as in previous years, by energy-intensive industries such as the production of metals, basic chemicals, paper, food and tobacco, and the processing of rock, earths and non-ferrous metals. In these industrial sectors, the provision of process heat and mechanical energy accounts for around 85% of the energy consumption. This applies basically for the whole of industry.

The main sources of energy for supplying industry

The most important final energy sources for supplying industry in Germany today are to an almost equal measure fossil gases and electrical energy, and then coal. These three energy sources make up roughly 80% of energy supplies; the remaining 20% is spread amongst mineral oil (declining), district heating, renewable and other energy sources.

Slightly more than two-thirds of electric energy is used to generate mechanical energy. Fossil gases are the main sources used to cover heating demand. Electrical energy is the only viable source of energy for refrigeration processes, mechanical energy, ICT and lighting.

The total consumption of electrical energy in Germany was approximately 519 TWh in 2012. Industry accounted for approximately 226 TWh or 43.5% of this. Homes consumed 27%, and Commerce, Trade and Services 26.4%. Transport only had a share of 3.2%.

In the years from 2008 to 2012, there were no fundamental changes in the structure of the energy consumption by the different application areas. Nor did the final energy consumption change significantly in these years. Only in 2009 did the significantly reduced levels of new orders resulting from the financial crisis in 2007 makes themselves felt in industrial energy consumption.

3.4.2 "Small industrial firm" energy cell

Description

Small industrial firms are somewhat larger than the companies described in the previous chapter concerning the CTS energy cell, but are similar to these in their behaviour. This type of firm represents a typical example of a medium-sized company that is often located in industrial areas outside urban centres.

Table 7 shows the characteristic parameters of this cell with regard to number of employees, peak power, energy consumption and mobility.

Table 7: Typical data of a small industrial firm (own assessment)

Characteristic	Unit	Value
Number of employees	-	~50
Max elec. connected load	kW	50-100
Annual elec. energy requirement	MWh/a	40
Annual heating requirement	MWh/a	130
Mobility requirement	-	7-10 vehicles
Own generation	kW	100-200

Typical load profiles for the Industry energy cell show similar profiles on weekdays and lower consumption on Sunday. Thus, the load profiles are very similar to those of the CTS energy cell. Standard load profiles cannot be used for industrial companies because of their great differences. It is the individual production process which determines the demand and the resulting performance profile.

Also, the heat load profile cannot be given as a default profile as, here too, there are large differences in the heat requirement and the peak periods. Statements therefore can only be made on a firm-by-firm basis following an analysis.

Consumption, production and storage of energy

The technologies listed in Table 8 can be used to supply energy to the "Small industrial firm" cell.

Table 8: Industrial firm cell equipment

Converters	Technologies	Potential
Energy-supplying converters	Diesel generator	Ready for use
	Photovoltaic system	Cost reductions expected
	Biogas plant	Ready for use
Energy-conditioning converters	Fuel cell	High development costs
	Inverters	Ready for use
Energy-extracting converters	Motor load	Ready for use
	Chemical process	Ready for use
Storage	Thermal storage	Ready for use
	Battery	Cost reductions expected

Figure 5 shows the energy flows for the cell with the various forms of energy.

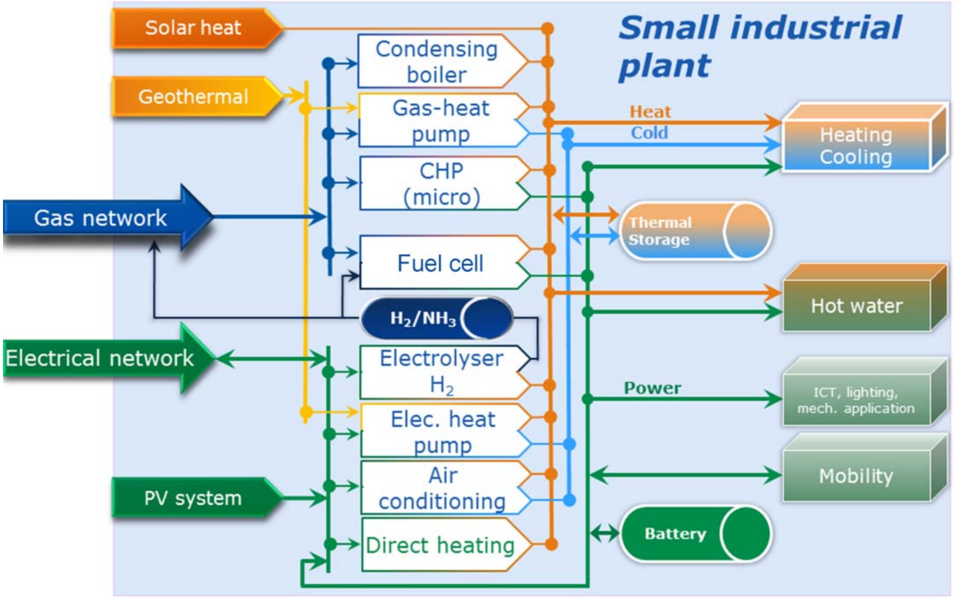

Figure 5: Energy and technology portfolio for the small industrial firm energy cell

Future requirements and approaches

In the future these cells will be subject to the following requirements and objectives, however these only differ slightly from the requirements of today's companies:

- Cheap energy procurement
- Reduction of energy requirement
- High supply reliability
- Environmental friendliness

As a result, most requirements can be derived from purely economic considerations. These goals can be achieved through various measures, such as

- Plant and cost optimization
- Increasing the share of electrical energy
- Demand-side management

In most cases, flexibilization of the load will only be possible to a very limited extent, since the electrical and thermal loads are tailored to the production process and therefore usually only a small percentage of the load can be influenced.

3.4.3 "Industrial area" energy cell

Description

Different combinations of a large number of small industrial firms and commercial companies as well as other types of business from the CTS energy cell; can represent the behaviour of an industrial area in various formations. They are often located outside urban centres. However, in the future a parent operator or provider for this cell will be able to optimize energy consumption and its procurement or its own generation.

Table 9 contains the most important characteristic parameters of this in terms of employee numbers, peak power and energy requirements as well as mobility.

Table 9: Typical data of an industrial area (own assessment)

Characteristic	Unit	Value
Number of employees	-	200-1,000
Max elec. power	MW	5
Annual elec. energy requirement	MWh/a	1,000-2,000
Annual heating requirement	MWh/a	3,000
Mobility requirement	-	50-200 vehicles
Own generation	MW	5-10

Figure 6 shows typical load profiles for electric power over one day and one week. These show uniform electricity demand between 07:00 and 18:00 which is almost identical from Monday to Friday but which is in stark contrast to the weekend.

Standard load profiles for the electricity or the heat requirement are not applicable due to the great differences.

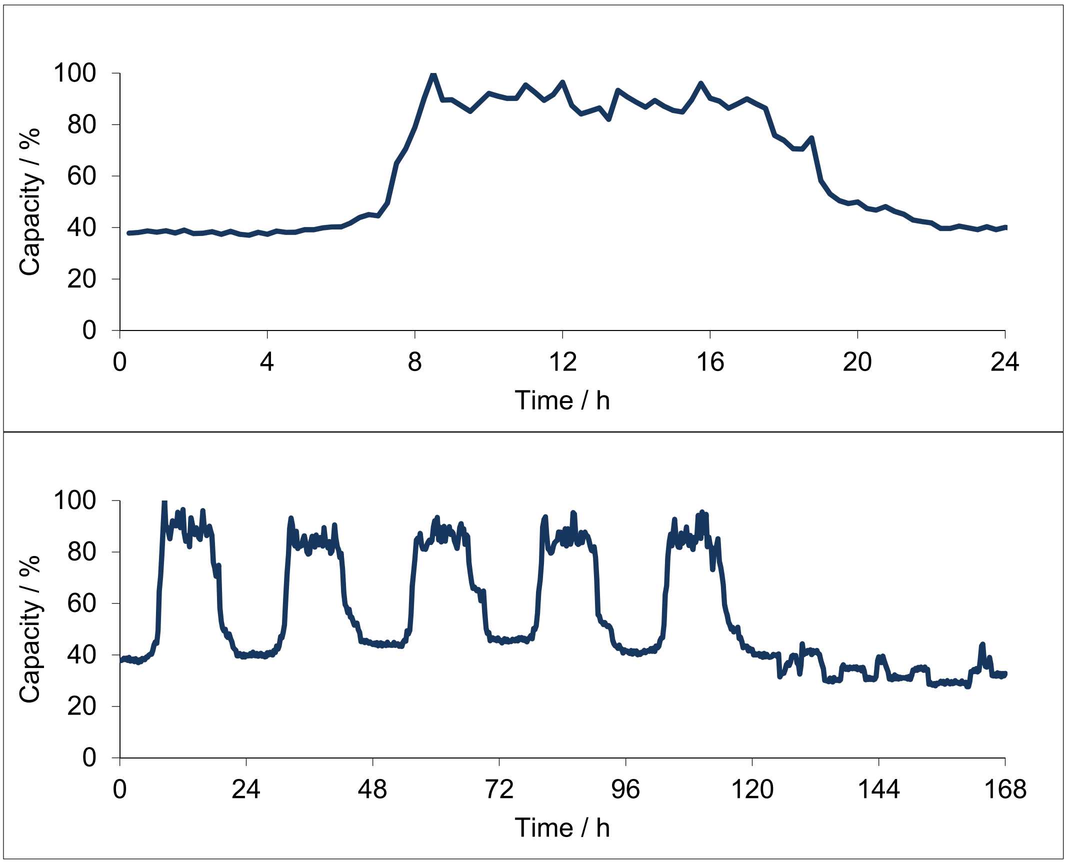

Figure 6: **Typical load profiles of the industrial area energy cell**

Consumption, production and storage of energy

Table 10 shows possible technologies for the energy supply of an industrial area. There is only low demand for heat and gas and it is limited to hot water and natural gas for small gas turbines, micro turbines and gas combination boilers.

Table 10: Industrial area energy cell equipment

Converters	Technologies	Potential
Energy-supplying converters	Diesel generator	Ready for use
	Wind power plant	Ready for use
	Photovoltaic system	Cost reductions expected
	Biogas plant	Ready for use
Energy-conditioning converters	Fuel cell	High development costs
	Electrolysers	High development costs
	Inverters	Ready for use
Energy-extracting converters	Motor load	Ready for use
	Chemical process	Ready for use
Storage	Thermal storage	Ready for use
	Battery	Expected reduction of costs
	Hydrogen storage	High development costs

Figure 7 shows the energy flows in the industrial area cell with the various forms of energy.

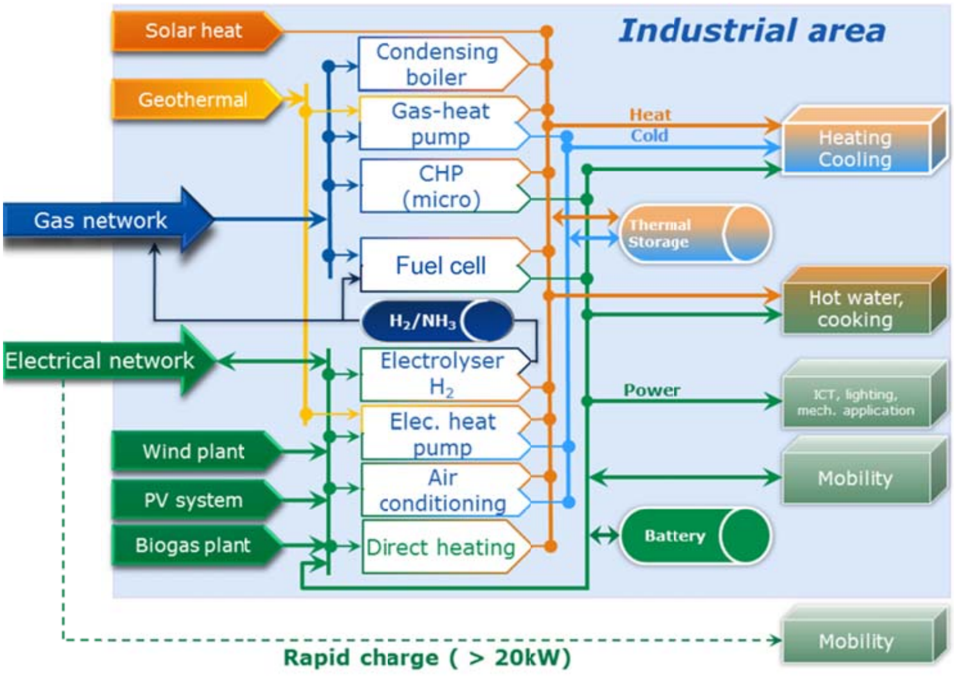

Figure 7: Energy and technology portfolio for the industrial area energy cell

Future requirements and approaches

The requirements and objectives of the industrial area energy cell are no different from those of the small industrial plant energy cell.

As with the industrial plant, flexibilization of the load is very limited. This includes e.g. larger loads from thermal energy requirements with inherent or additional built-in storage capacity.

From the load profile it can be seen that the generation profile of PV systems is well matched to the consumption and can thus make a significant contribution to covering a part of the electrical load locally.

The solutions can be complemented by additional measures. Here, too, the measures are determined today and in the future almost exclusively by economic considerations, such as

- Reduction of power peaks
- Increase in efficiency and reduction of conversion losses
- (Temporary) Operation as island or micro networks
- Use of waste heat/cogeneration

3.4.4 "Industrial park" energy cell

Description

The industrial park energy cell is typified by large industrial plants which have a huge requirement for process heat in particular. As shown in Table 11, the demand for electric power is also very high.

Typically, these large plants have their own power stations which generate heat in addition to electric power (combined heat and power, CHP). The generation plants are often run as gas and steam plants. Gas networks are frequently installed on the industrial park for the energy supply and the various industrial processes,. The companies also require more sources of energy and raw materials, such as hydrogen in the chemical industry.

The energy requirement and resulting generation plants depend on the type of production facilities. This can only be represented here as an example. Only a detailed analysis of individual industrial parks can provide more detailed parameters.

Table 11: Typical data for the industrial park energy cell (own assessment)

Characteristic	Unit	Value
Number of employees	-	several 1,000
Max elec. Power	MW	500-1,000
Annual elec. energy requirement	GWh/a	3,000-7,000
Annual heating requirement	GWh/a	6,000-20,000
Mobility requirement	-	200+ vehicles
Own generation	MW	200-500

Figure 98 shows a typical load profile of an industrial park energy cell for one day and one week. It can clearly be seen that there is little fluctuation throughout the day and that there is no difference between weekdays and the weekend or Sunday.

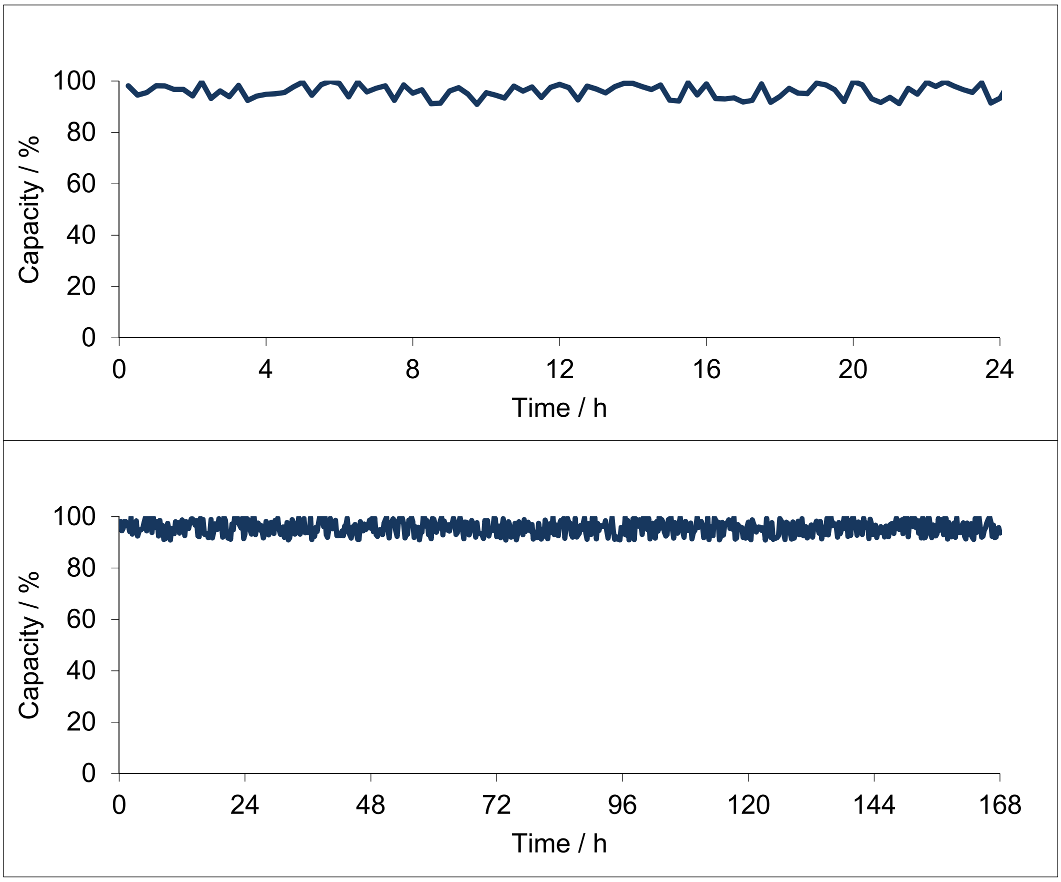

Figure 8: **Typical load profile of the industrial park energy cell**

Consumption, production and storage of energy

Possible technologies for the energy supply of an industrial park are shown in Table 12. In contrast to the "small industrial plant" and "industrial area" energy cells described above, there is significantly greater demand for heat here than for electricity.

Table 12: Industrial park cell - equipment

Converters	Technologies	Potential
Energy-supplying converters	Gas turbine	Ready for use
	Cogeneration	Ready for use
	Wind power plant	Ready for use
	Solar thermal energy	Costly
Energy-conditioning converters	Fuel cell	High development costs
	Electrolysers	High development costs
	Inverters	Ready for use
Energy-extracting converters	Motor load	Ready for use
	Process steam	Ready for use
	Chemical process	Ready for use
		Ready for use
Storage	Thermal storage	Ready for use
	Natural gas storage	Ready for use
	Hydrogen storage	High development costs

Figure 9 shows the energy flows for the cell with the various forms of energy.

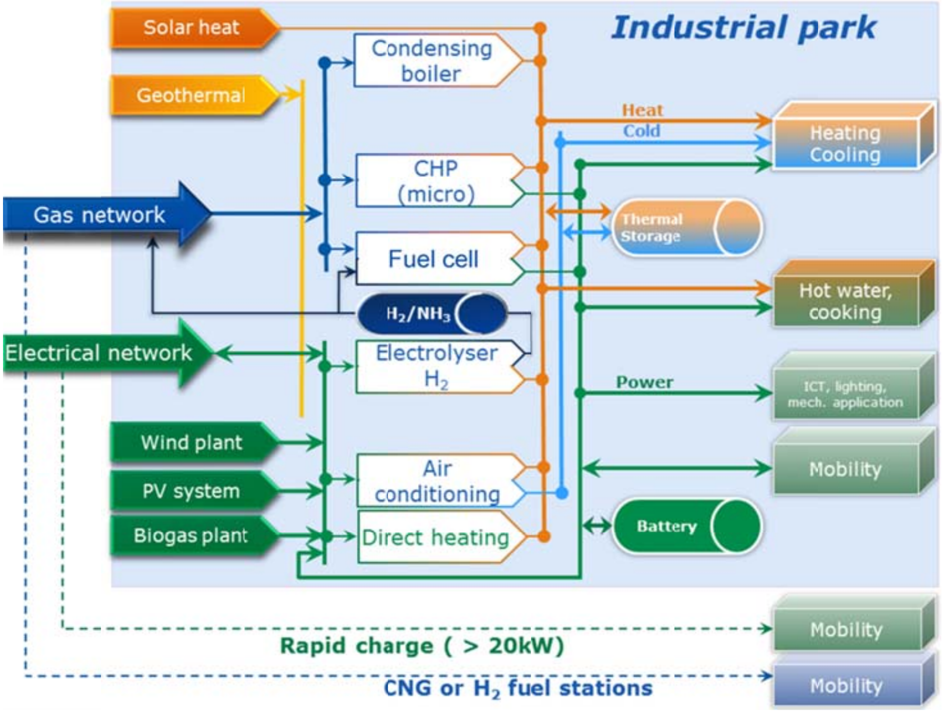

Figure 9: Energy and technology portfolio for the industrial park energy cell

Future requirements and approaches

In the future this cell will be subject to the following requirements and objectives. However, these only differ slightly from the situation of today's companies:

- Cost-effectiveness / cheap energy procurement
- Increased efficiency of all process operations
- High degree of reliability

- Different primary energy sources

Due to their enormous demand for electricity and gas, industrial parks will in the future continue to rely on a connection to the gas and electricity transmission networks. Yet gas and electricity as forms of energy in very large quantities only have limited compatibility for large-scale industrial plants, i.e. they cannot replace, only complement each other.

It can also be assumed that the energy consumption characteristics of large industrial parks will not change much in the future and that they will depend on the production processes as they do today. The final energy consumption of industry will decrease slightly as a result of further energy efficiency improvement measures. Electricity consumption will remain virtually unchanged, however, thus gaining in importance in the industry energy mix [11]. Appropriate technical solutions are already available, however industrial companies will always base their decision of whether to use them on purely economic factors. Exempt from this are sensitive technical processes and processes for the production of essential parts.

As a result, most requirements can be derived from purely economic considerations. These goals can be achieved through various measures, such as

- Reduction of power peaks
- Own generation
- Reduction of conversion losses
- (Temporary) Operation as an industrial island network
- Load and generation control based on a predetermined timetable

3.4.5 Interim result for Industry energy cell

The final energy consumption of industry is characterized mainly by the production processes of the individual sectors and companies. The main priorities are meeting the heat requirement, which accounts for around three quarters of the consumption, and providing mechanical energy, representing around one-fifth of the total energy requirement.

Fossil gases and electricity are the main energy sources for industry today. Electricity is mainly used to generate mechanical energy whereas fossil gases serve primarily to generate process heat. In the near future it is expected that fossil gases will gradually be replaced by biogases and methane created in power-to-gas plants (methanation) and hydrogen (electrolysis), however this will have no immediate effect on the fundamental design of the distribution networks. The replacement of other fossil fuels which are important for industry such as oil and coal for the local generation of space heat and hot water by electric energy (power-to-heat) generated from local renewable energy sources (photovoltaic and wind) is becoming increasingly important in industry. The proportion of electrical energy will therefore increase in the energy mix of Industry cells.

It can be concluded that the greater the cell size and thus the higher supply energy intensity, the less it will be possible to meet the energy requirement locally from renewable energy sources. For the basic design of new networks this means that small and medium-sized industrial cells in the future will have to rely on a connection to the electrical network and/or gas distribution network, and large industrial cells will depend on the gas and/or electricity transmission grids.

3.5 Overall result for the cellular approach

The investigations conducted in this study show that the autonomous supply of energy cells is only possible for homes and selected energy cells in the services sector. The other energy cells - CTS and in particular Industry - require a network, at least at the regional level. The extent to which large-scale energy transmission is required can be assessed based on the investigations in the next chapter.

Both gas and electrical networks are available for the networking of energy cells. Much greater strain may be placed on electrical networks. This can be mitigated by the demand side management of storage systems and loads and the resulting homogenization of the load. In gas networks, new levels of flexibility can be achieved if bidirectional flows and flexibility in the spatial and temporal characteristics and in the type of gas are exploited.

Increased demand for transmission is created by the integration of renewable energy sources. This can be reduced by the cellular approach.

The cellular approach supports and requires a new market design and business models. These have already been explored in the VDE studies on active energy networks in the context of the energy transition [12] and on flexibility markets [13].

Finally, the question remains of who assumes responsibility for the resulting overall system and for bringing this in line with the new framework conditions.

4 Fundamental considerations on supra-regional energy balancing

As pointed out in chapter 3, it is not possible to achieve self-sufficiency in all energy cells. Industry, large cities, conurbations, but also cities with dense development cannot meet their energy needs in sufficient quantities locally. These energy cells are therefore reliant upon energy imports. The amounts of energy needing to be transferred in a year in Germany in the future are estimated in examples based on two different approaches with different degrees of cellular structure.

Since both approaches are based on assumptions, these are not represented in detail here. Statements on the forms of energy used, energy transmission systems or even system-specific constraints could only be made based on a large number of other assumptions and are not considered here.

4.1 Method

The method for determining the transmission corridors and the transmission capacity that can be derived from the assumptions described in the preceding chapters is described below.

As stated in section **Fehler! Verweisquelle konnte nicht gefunden werden.**, it is assumed for the purpose of the investigations that the annual demand for electricity in Germany will increase in the future. An average net demand of 700 TWh/a was used for the following calculations. In the model investigation, this amount of energy is supplied entirely from renewable energy sources in Germany (divided into regions).

The method consists of five steps. Regions (4.2) are defined with connecting corridors (4.3) between them. Each region is assigned a requirement (4.4) and a provision (4.5) of electrical energy. Following optimization, the transmission corridors (4.6) are found via which the energy is actually transmitted.

The result clearly shows how much energy must be exchanged between neighbouring regions.

4.2 Regions

The regions are defined in the first step. The federal states, as well as the North Sea and the Baltic Sea are designated as regions. For simplification, Berlin and Brandenburg, and Bremen and Lower Saxony are each combined, resulting in 16 regions. Extension to include smaller units such as administrative regions or districts is not required for this investigation. Furthermore, the coarse resolution enhances the clarity and transparency of the method and its results.

4.3 Connection corridors

In the second step, the connection corridors are determined which, in combination, form an overlay network. Connecting corridors are direct connections between neighbouring regions. Each region has a central transfer point where the overlay network is connected to the subordinate network. The transition points on land are located in the key areas of each region. In the North Sea and Baltic Sea, the transfer points correspond to the centres of the existing and planned offshore wind power plants. From these points Delaunay triangulation [14] is used to create a triangular network of connection corridors. Figure 10 shows the resulting connection corridors and their lengths.

4.4 Assumptions regarding electric energy demand

In the third step, the annual demand for electrical energy is assigned to each transfer point. It is assumed that in the future the increased net requirement of 700 TWh/a will be spread to the regions proportionately to the reference year 2011. The area within the black circle lines in Figure 12 and Figure 13 shows the demand for electrical energy in the regions.

4.5 Assumptions regarding the provision of electrical energy

In the fourth step, the 2011 EEG statistical report [15] serves as a starting point for the investigation of future energy supply. Based on this, two approaches are examined which assume the same energy requirement. The largest part at 610 TWh/a is provided in both approaches by PV systems as well as onshore and offshore wind plants, however the spatial and quantitative breakdowns differ. The share of energy from biomass power plants increases from approximately 28 to 60 TWh/a, and that of water from about 5 to 30 TWh/a. The small contribution made by geothermal energy and landfill, sewage and mine gas is ignored. The composition of electrical energy supplied per region can be seen in Figure 12 (approach A) and Figure 13 (approach B).

4.5.1 Approach A

In Approach A there is a continuing increase in renewable energies, including a massive expansion of offshore wind plants. Following the energy concept of the Federal Government, capacities of 40 GW are set for the North Sea and 10 GW for the Baltic Sea. Assuming 4.500h/a full-load hours, this means that 225 TWh/a can be supplied. For the remaining requirement of 385 TWh/a, the installed capacity of the PV systems and onshore wind plants from 2011 from Table 13 will be increased until the demand can be met. All the land-based plants are assigned to the regions proportional to the distribution in 2011. Figure 12 shows the regional energy supply by energy source, and the energy requirement.

4.5.2 Approach B

In contrast to approach A, approach B aims to expand renewable energy generation in the proximity of consumers. It therefore only includes moderate increases in offshore wind farms. A capacity of 10 GW is set for the North Sea and 2.5 GW for the Baltic Sea. At 4,500 full-load hours this corresponds to an energy of 56.25 TWh/a. The potentially usable area for the required PV systems and onshore wind plants is

assessed. The area data of the individual regions are taken from CORINE Land Cover 2006 (CLC06) [16].
Three types of area are designated for PV installations: 10% of the *continuous urban fabric*[6] area will be given over to PV systems. For example, approximately 1% of Hamburg has a *continuous urban fabric*. PV plants will be installed in 5% of the ground area of *discontinuous urban fabric* areas, rising to 25% in *industrial or commercial units*.
An area-related capacity of 0.1 kW_p/m^2 and 1,000 h/a full-load hours are determined for all PV systems. Based on these assumptions, 176 TWh/a will be fed in in Germany. The remaining 378 TWh/a must be provided by onshore wind plants.
A mean wind speed is calculated for each region from wind data supplied by the German Meteorological Service [17]. Based on the simplified assumption that wind plants are operated at the mean wind speed, the expected annual energy per wind plant can be deduced from the performance characteristic. The CLC06 categories *arable land* and *pastures* are designated for the installation of wind turbines. The energy required can be supplied if 0.7 WT/km^2 are installed nationwide on *arable land* and 0.2 WT/km^2 are installed on *pastures* throughout Germany. The regional supply of energy by energy source, and the energy requirement can be seen in Figure 13.

A list of the feed-in energy using both approaches by region is contained in Table 14.

A comparison of electricity requirement and consumption is shown in Figure 11.

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[6] As defined in [16]

Table 13: Feed-in energy 2011 from renewable energy systems in GWh [15][7]

	Hydroelectric plants	Biomass power plants	Landfill, sewage, mine gas	Geothermal power	Onshore wind plants	PV plants	Offshore wind plants	Total
Baden-Wurttemberg	1217	2865	54	0	628	3288	0	8052
Bavaria	2370	5653	30	8	778	7147	0	15986
Berlin	0	142	0	0	6	36	0	184
Brandenburg	16	2052	143	0	7886	776	0	10873
Bremen	0	23	1	0	257	13	0	294
Hamburg	0	154	1	0	82	13	0	250
Hesse	214	920	62	0	886	944	0	3026
Mecklenburg-Vorpommern	9	1576	31	0	3087	264	0	4967
Lower Saxony	196	5385	50	0	12145	1486	0	19262
North Rhine-Westphalia	224	2883	865	0	4880	2025	0	10877
Rhineland-Palatinate	107	691	30	11	2105	940	0	3884
Saarland	34	45	387	0	220	179	0	865
Saxony	266	1061	42	0	1653	637	0	3659
Saxony-Anhalt	85	1498	77	0	6159	523	0	8342
Schleswig-Holstein	9	1809	23	0	6190	735	0	8766
Thuringia	97	1222	16	0	1349	341	0	3025
North Sea	0	0	0	0	0	0	443	443
Baltic Sea	0	0	0	0	0	0	125	125
Total	**4844**	**27979**	**1812**	**19**	**48311**	**19347**	**568**	**102880**

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[7] The source only includes renewable energy systems and is used primarily as a measure of the spatial distribution of the plants across the regions. The amount of energy fed in by all hydroelectric power plants (including non-renewable) is many times higher. [18] More recent *Länder* figures were unfortunately not available at the time of publication.

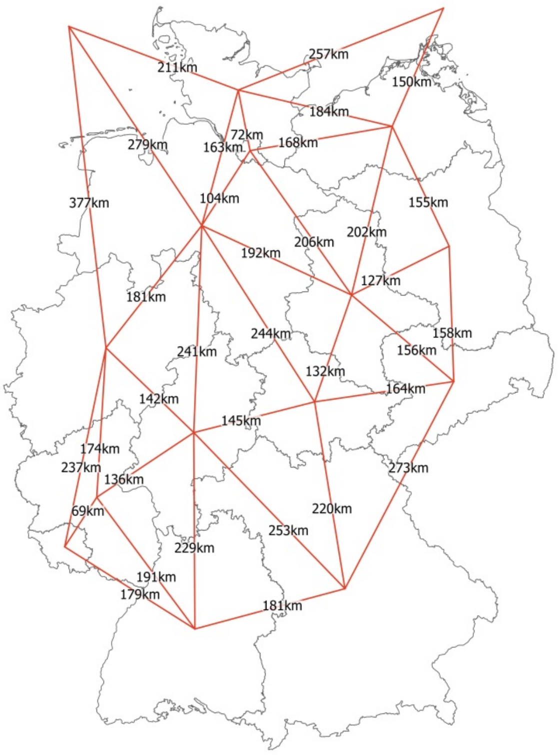


Figure 10: **Inter-region connection corridors and their lengths**

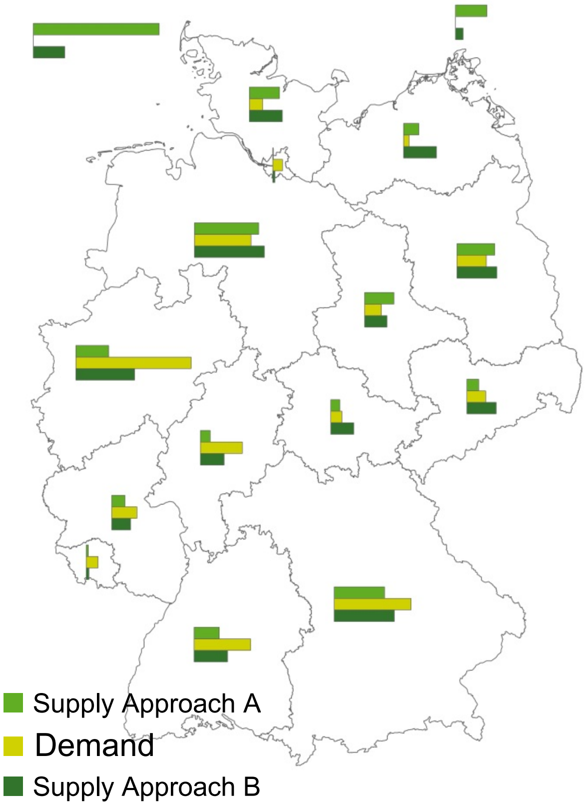
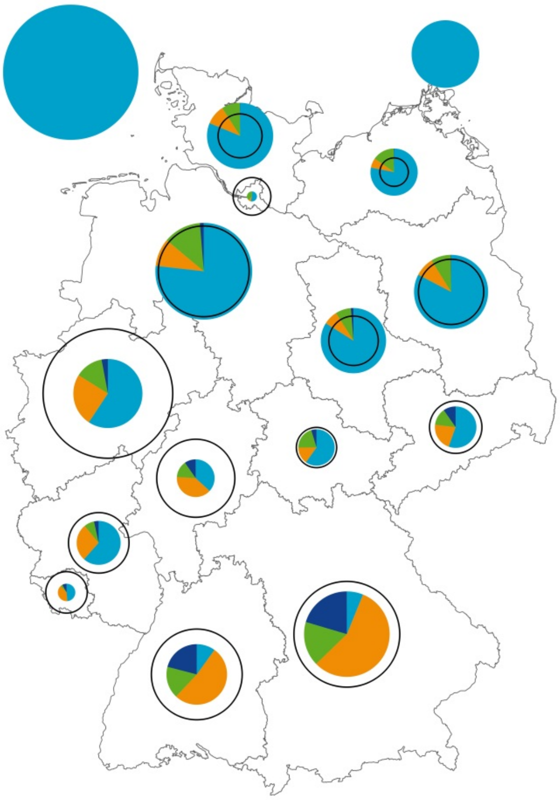
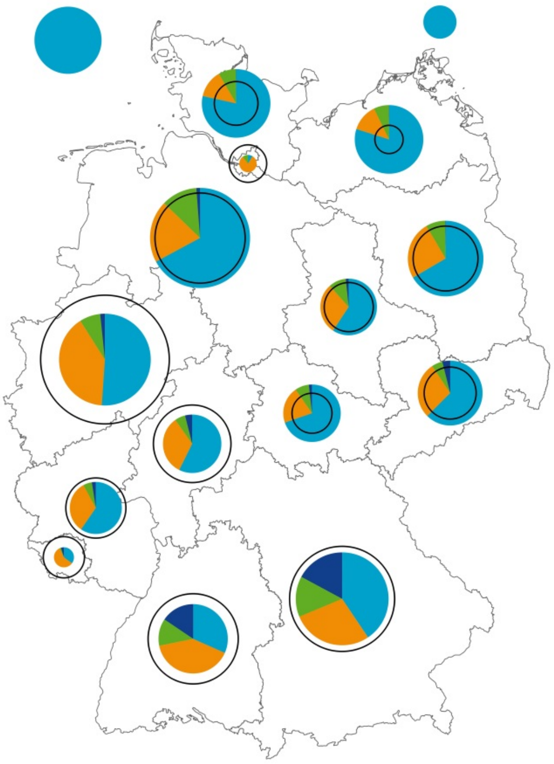


Figure 11: **Demand and supply based on investigated approaches A and B**





Energy supply: 🟦 Wind 🟧 PV systems 🟩 Biomass plants ■ Hydroelectric plants
Energy requirement: ○ (circle line)

Figure 12: Approach A - Supply and demand by region (massive increase in off-shore wind plants and linear increases on land since 2011)

Figure 13: Approach B - Supply and demand by region (moderate increase in off-shore wind plants and increase on potential areas of mixed land)

4.6 Transmission corridors

In the fifth and final step, it is calculated which connection corridors are to be used to balance energy for the chosen assumptions. Energy supply and intake must be balanced at each transfer point. The result is a system of linear equations which is optimized to minimize the total product of transmitted energy and length across all corridors. This meets the target of transmitting as little energy as possible over the shortest possible distances. As a result, no energy is transmitted through many corridors. All other connection corridors are used and are therefore referred to as transmission corridors. The resulting transmission corridors are shown in Figure 14 and Figure 15.

In both approaches energy must be transmitted from North to South and from East to West. In Approach A, significant amounts of energy must be transmitted from the North Sea to North Rhine-Westphalia. The required transmission corridor must have a transmission capacity of 180 TWh/a and a length 377 km. The greatest transmission challenge in Approach B is 64 TWh/a over a distance of 145 km between Hesse and Thuringia.

602 TWh of energy must be balanced per year in Approach A; this figure is only 394 TWh in Approach B. Thus, only 55% of the amount of energy transmitted in Approach A must be transmitted in B.

The energy figures can be weighted to include the length of the transmission corridor. In Approach A this results in 141,390 TWh km/a, and in Approach B in 78,936 TWh km/a. Thus, it can be shown that Approach B reduces the expenditure involved in balancing energy by approximately 45%.

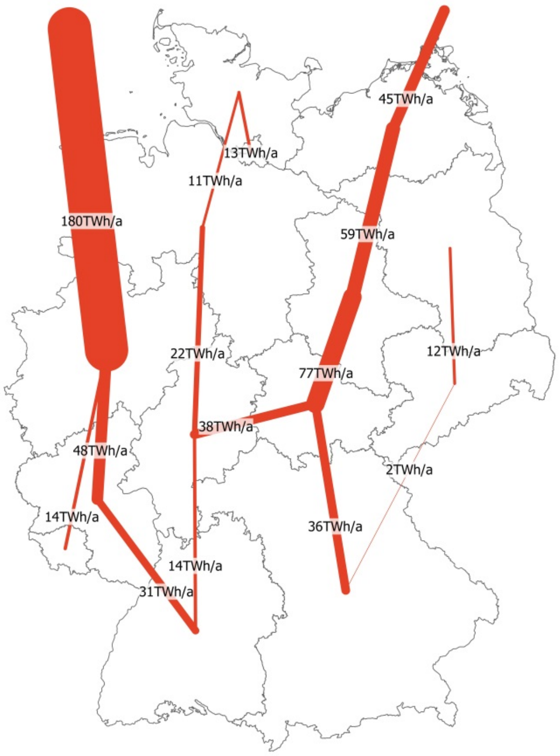


Figure 14: Approach A - Transmission corridors with required annual energy balance

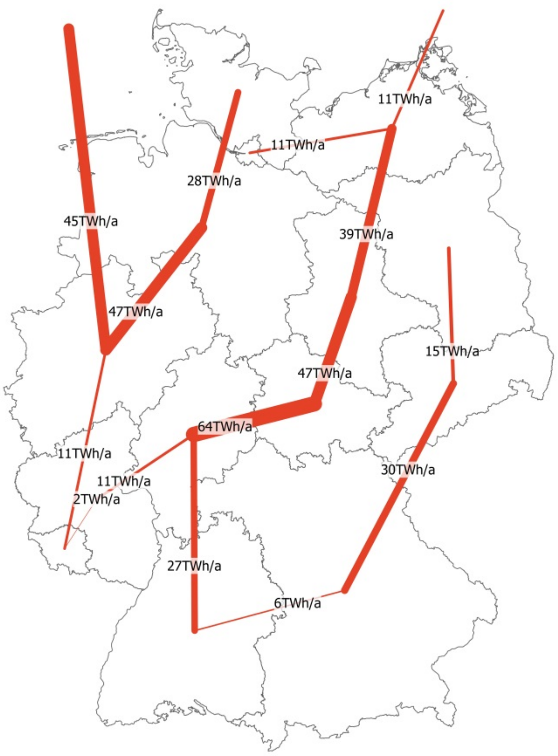


Figure 15: Approach B - Transmission corridors with required annual energy balance

Table 14: Fed-in energy in the future scenario in GWh

	Hydroelectric plants	Biomass power plants	Photovoltaic systems		Wind plants		Total	
			Approach A	Approach B	Approach A	Approach B	Approach A	Approach B
Baden-Wurttemberg	7537	6144	18710	19447	3574	15322	35965	48450
Bavaria	14678	12123	40669	24104	4427	34738	71897	85643
Berlin-Brandenburg	99	4705	4621	14095	44908	37693	54333	56593
Hamburg	0	330	74	2539	467	271	871	3140
Hesse	1325	1973	5372	10990	5042	19189	13712	33477
Mecklenburg-Vorpommern	56	3380	1502	6092	17566	37820	22504	47348
Lower Saxony - Bremen	1214	11597	8530	20084	70572	67163	91913	100058
North Rhine-Westphalia	1387	6182	11523	33430	27769	42816	46861	83815
Rhineland-Palatinate	663	1482	5349	8749	11978	16057	19472	26950
Saarland	211	97	1019	2485	1252	1506	2579	4300
Saxony	1647	2275	3625	11802	9406	26194	16953	41918
Saxony-Anhalt	526	3212	2976	9357	35047	19090	41761	32185
Schleswig-Holstein	56	3879	4182	6131	35223	36629	43340	46695
Thuringia	601	2621	1940	6846	7676	23176	12838	33244
North Sea	0	0	0	0	180000	45000	180000	45000
Baltic Sea	0	0	0	0	45000	11250	45000	11250
Total	**30000**	**60000**	**110092**	**176151**	**499907**	**433914**	**700000**	**700000**

4.7 Result

Based on different assumptions, the method presented shows how much energy needs to be supplied and balanced to meet the demand for electrical energy entirely from renewable energy sources. The required energy balance and thus the demand for transmission capacity varies significantly between the two approaches due to the spatial distribution of the energy supply. The fact that energy balancing is required in both approaches also shows that the energy transition can be implemented not only on the regional scale, i.e. at the level of the Länder, as is the case today. A supra-regional approach to energy supply and energy transfer is now of paramount importance.

Energy transmission and energy transportation options were not addressed in this investigation. The study [4] carried out by RWTH Aachen offers a clear analysis of this.

5 Summary

The further development of small decentralized generation units with up to an 80% share of renewable energy means that new energy network structures are required. The present study investigates to what extent it is possible to balance the consumption and generation of energy locally. The aim is to keep the exchange with neighbouring cells and regions to a minimum, resulting in a correspondingly low demand for line capacity. This approach makes widespread use of new technologies for the generation, conversion and storage of energy in the cheapest form in each case, where these technologies either already exist or their application is foreseeable.

In this cellular approach, so-called energy cells are formed in which the energy balance, as well as the exchange of energy between them can be planned and controlled. The local energy cells are connected to each other by energy networks and communication systems to form larger energy cells. These larger energy cells in turn have the interfaces and properties described in this study. The combining of energy cells takes place at multiple levels. The cellular approach can be applied both to small and larger units and systems. A complete energy cell consists of the following components: generators, converters, storage facilities, network connections, loads and protective and I&C equipment. Subsets of energy cells are also possible; these can be used e.g. to describe conventional systems.

From an energetic viewpoint, there are over and underbalanced energy cells, and also - ideally - balanced energy cells, although this is not possible for all energy cells due to insufficient local generation. These under-balanced energy cells require energy from over-balanced cells. It is therefore apparent that energy transfer between multiple energy cells is required to create a balance despite the cellular approach. The application of this concept leads to the following main results and conclusions of the study.

5.1 Conclusions

The cellular approach - basis for sustainable power supply development

Cellular approaches are already being used successfully today, for example in communication technology. In energy supply, too, the cellular approach represents a consistent system-wide development of the existing practice of distributed energy generation, conversion and local storage. In this approach, greater convergence of different energy sources is explicitly taken into account and made possible.

In the cellular approach, the aim in the future will be to balance local generation and consumption at the lowest feasible levels. Crucially this allows the special characteristics of renewable sources of energy to be taken into account and integrated optimally into the energy supply system.

The investigations showed that the local balancing of generation and consumption in the individual energy cells significantly reduces the amount of energy transfer required.

The cellular approach - Technical innovation and driving force behind electrical energy supply from renewable energy sources

The cellular approach gives rise to active subsystems which can respond in an appropriate manner to the demands of the higher-level system. This results in new options for the operation of energy systems, ranging from the provision of system services to the temporary autonomous operation of subsystems. This concept inherently helps increase the robustness of the overall system in terms of system stability and reliability of supply. In addition, prosumer confidentiality is ensured by the aggregation and resulting anonymization of the data.

The local balancing of generation and consumption reduces the demand level of the entire energy system caused by the volatile nature of renewable energy generation. This greatly simplifies the integration of renewable energy sources into energy supply systems. The cellular approach therefore forms the basis of a sustainable renewable energy-based energy supply in the future.

The cellular approach permits the gradual transformation from the existing to a new energy supply system. As a result, both systems can be operated in parallel during the transitional period.

The cellular approach - Supporting energy source convergence

The cellular approach is characterized by its accommodation of all energy sources, as well as new technologies. The technical implementation is independent of the energy source, e.g. gas or electricity, and of the energy conversion and storage technologies used. Each energy source has specific advantages and disadvantages which can be optimally exploited in the cellular approach.

Thus, the advantages of electrical energy are that it can be transformed very simply and (normally) highly efficiently into all other forms of energy and that it is regarded, in combination with renewable generation, as a very clean form of energy. The great disadvantage is that electrical energy cannot be readily stored, meaning that other forms of energy must be used for this. In addition, the construction of new electrical lines often meets with resistance.

As an energy carrier, gas is very easy to store, and short-term power fluctuations can be buffered directly through the inherent storage capacity of the gas network itself. Long term gas storage is easy to implement. The main disadvantage of gas as an energy carrier is that its conversion into electricity is relatively inefficient. Also "regenerative" gas can only be created using electrolysis powered by electricity.

Thermal energy is cheap and easy to store. The disadvantages are that conversion into other forms of energy is inefficient and that transmission over medium and long distances makes little sense because the losses are too high.

The optimum energy source for each task can be deployed through use of appropriate conversion technologies. Large-scale solutions in higher-level power cells as well as technical solutions at the local level can then be applied.

These solutions are characterized by their high degree of flexibility in response to technical, economic or regulatory changes.

The cellular approach - Basis for long-term acceptance of the power transition
The cellular approach establishes a direct link between the users and the necessary energy supply technology as a result of the local allocation. It has become apparent in the past few years that this has significantly increased acceptance levels.
Also, users at the local level have a high degree of self-determination thanks to the flexibility of the system. Users can decide themselves how much of which technologies are to be used and to what extent system-supporting services are offered by the energy cells.

The cellular approach - Permits a reduction in energy transmission
The reduction of the residual load of the energy cells through the cellular approach reduces the amount of energy transmission required. The cellular approach allows generation and consumption to be balanced within one cell and between neighbouring cells at the local level. However, this local balancing is only possible to a limited extent; commercial and industrial energy cells and also those of densely populated residential areas are usually dependent on energy imports. Furthermore, the spatial separation of generation plants in the North and consumption areas in the South means that energy transport is still required in Germany.

The cellular approach - Engine driving economic growth and new market models
The cellular approach allows the development of new business models and markets. Through clearly defined energy cell interfaces, energy cells can be operated and technology selected and installed by new service providers or investors in the market.

5.2 Recommended action

The study results presented here yield the following recommendations:

- Development plans for future energy networks at all levels must take into account all types of energy such as electricity, gas, heat, etc.
- The development of storage technologies across a wide energy spectrum must continue to be supported to advance the integration of renewable energies in the energy system.
- The development of efficient conversion technologies must be encouraged, to exploit the advantages of different forms of energy.
- Further research is needed to clarify open questions of responsibility for the planning and operation of the overall system in the implementation of the cellular approach.
- Field tests are proposed to assess the viability of the cellular approach.

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Abbreviations

BHKW	Blockheizkraftwerk (*combined heat and power plant, CHP*)
BMWi	Bundesministerium für Wirtschaft und Energie (*Federal Ministry for Economic Affairs and Energy*)
CLC06	CORINE Land Cover 2006
DSM	Demand Side Management
GHD (CTS)	Gewerbe, Handel und Dienstleistungen (*Commerce, Trade and Services*)
IKT	Informations- und Kommunikationstechnologie (*ICT - Information and communication technologies*)
Power2Gas	Conversion of electrical energy to gas
PSW	Pumpspeicherkraftwerk (*pump storage power plant)*
PV	Photovoltaik (*photovoltaic*)
TF	Task Force
WEA	Windenergieanlage (*wind power plant*)

Glossary

Energy

Primary energy sources are sources that are found in nature.

for example, crude oil, coal, natural gas, hydropower, wood, biomass, wind, solar radiation, etc.

Environmental energy... renewable primary energy

for example, hydropower, wood, biomass, wind, solar radiation, etc.

Secondary energy … is a form of energy which is based on primary energy and is used to facilitate transmission and storage of the energy.

e.g. mineral oils, coal coconut, electricity, etc.

Final energy ... Energy used by the end user.

e.g. see secondary energy

Useful energy... Energy which meets the needs of the customer.

e.g. heat, cold, light, mechanical energy

Energy converter ... Device or system in which energy is converted from one form to another is (e.g. gas to electricity, but also the conversion of pure electrical energy, such as altering the electrical voltage)

In this study, energy converters are subdivided into three types: converters supplying power to the balancing group, converters extracting power from the balancing group, and energy conditioning converters.

Prosumer ... Refers here to operators of energy cells which are simultaneously consumers and also producers of energy.

Annex 1: Technology profiles

This annex is only included in the German version of the study.

You can download it as an Excel document using the password abdefg from the following site: www.vde.com/kurzlink

Annex 2: Detailed investigations

This annex is only included in the German version of the study.

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