Chapter 2
System Interrelations Between Spatial Structures, Energy Demand, and Energy Supply

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Abstract Based on a system analysis of elements dealing with spatial structures, energy demand, and energy supply, the most effective regulatory elements for integrated spatial and energy planning are identified. Based on these regulatory elements, the connections between energy efficiency and spatial structures, renewable energy provision and spatial structures, as well as energy logistics and spatial structures, are discussed. Finally, this system analysis is complemented by principles derived from the concept of resilience against energy crises. This approach results in a set of regulatory elements and steering principles to pursue integrated spatial and energy planning.

In order to describe the highly complex system interrelations between spatial structures as well as energy demand and supply, we utilize a system analysis that was carried out in the research project PlanVision (Stoeglehner et al. 2011b). Therefore, systems are understood as explanations of reality, which define the relations of phenomena and influencing factors—hereafter called system elements. The selection of system elements and the identification of their interactions depend on the task of the respective survey. Therefore, systems are always bound to the human perception of complex issues with the following characteristics (Heizinger 1995; Röpke 1977):

- They are “holistic,” contrasting the reductionist logic of linear cause–effect relationships; system approaches move from the entity to the details, giving priority to the interrelations between the system elements instead of the detailed descriptions of single elements.
- They are “open,” so they are entities, which are in constant exchange with their environments, and their internal interactions are oriented on a common target of the system.
- They are eminent, which describes their property that interactions within the system can result in a new system behavior, which cannot be explained by the features and behavior of the single system elements. In other words, a system is more than the sum of its elements.

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In order to derive guidance for action from the system analysis, cybernetics was applied, which deals with the possibilities to steer and regulate complex systems, especially seeks for positive and negative feedback effects (Bertalanffy 1949; Wiener 1948; Vester 2007). Concerning ecosystems and organisms Vester (2007) defines, inter alia, the following main principles of biological cybernetics:

- Negative feedback effects have to dominate over positive feedback, e.g., to prevent uncontrolled growth such as cancer;
- The functioning of the system must be independent from quantitative growth;
- The system must be oriented toward function, not to production;
- Multi-shift use of products, functions, and organizational structures should be applied;
- Cycle processes should guarantee recycling.

Applying system's theory approaches in spatial contexts is an established practice (see, e.g., Vester 1983; Lippuner 2005) The system's theory approach in PlanVision was used to determine the system elements of spatial and energy planning based on the literature surveys, brainstorming, and reflection workshops carried out by an interdisciplinary research team of 19 researchers including disciplines such as landscape, spatial and environmental planning, engineering, energy technology, social sciences, macroeconomics, law, environmental system sciences, and transport science, as well as environmental and natural resource management. Group discussion results were visualized in mind maps (according to Buzan and North 2005; Stoeglehner et al. 2006) and analyzed. The process resulted in a set of 34 system elements stemming from the domains of spatial planning (19 elements) and energy planning (15 elements). In order to operationalize the search for the relevant relations between the system elements, an adapted "paper computer" (Vester 1976, 1980, 2007) was applied. The paper computer is a networking matrix that aims at quantifiable conclusions about the structure of a system and to identify the relevant steering elements of a system by making the impacts of a system element on all other system elements visible. According to their ability to impact other system elements and their exposure to being influenced by others, system elements can be classified into four categories:

- Active elements: These strongly impair other elements, but are only impacted weakly by others.
- Passive elements: These are strongly influenced by other elements and influence others to a small extent.
- Critical elements: These show a strong impact on other elements and are strongly affected by others.
- Buffering elements: These have low effects on others and are weakly affected by other elements.

Concerning the steering of a system, active elements are of high importance, because changing them has a high impact on the system, but the risk of unforeseen rebound effects is low. Starting with the change of critical system elements would also show high impacts, but as they are also influenced by many other elements the chance is high that unforeseen and uncontrolled effects can be detected throughout the system. Trying to change a system with passive or buffering elements is rather hopeless, as impacts on other system elements are weak, and the efforts for change would either be very high or blow out with little effect.

The original model after Vester judges the size of the effect in an ordinal scale and then sums and quotients are calculated. In this way, ordinal data are treated like metric data (Bortz 2005); furthermore, the reliability and inter-subjectivity of the method is not guaranteed, as the scaling of the effects is based on personal judgments and perceptions which are subject to permanent change. In order to overcome this methodological critique of the paper computer, in PlanVision it was determined if a relation between system elements exists (1) or not (0). In a first step, all researches had to judge the interrelations in the matrix. In a second step, all interrelations were discussed in workshops and the interdisciplinary team had to jointly agree on the classifications and reason them. The amount of relations of each system element was counted and then graphically evaluated which element belongs to which category of system elements.

Finally, out of the 34 system elements six turned out to be active, 7 elements to be critical, 13 to be passive, and 8 to be buffering. The system elements under survey and their assessment can be derived from Fig. 2.1. The system elements can be used to analyze policies, legal frameworks or plans if objectives and measures address the active and critical elements, or if they target system elements, which are to be called passive or buffering in a holistic systems analysis. By carrying out such

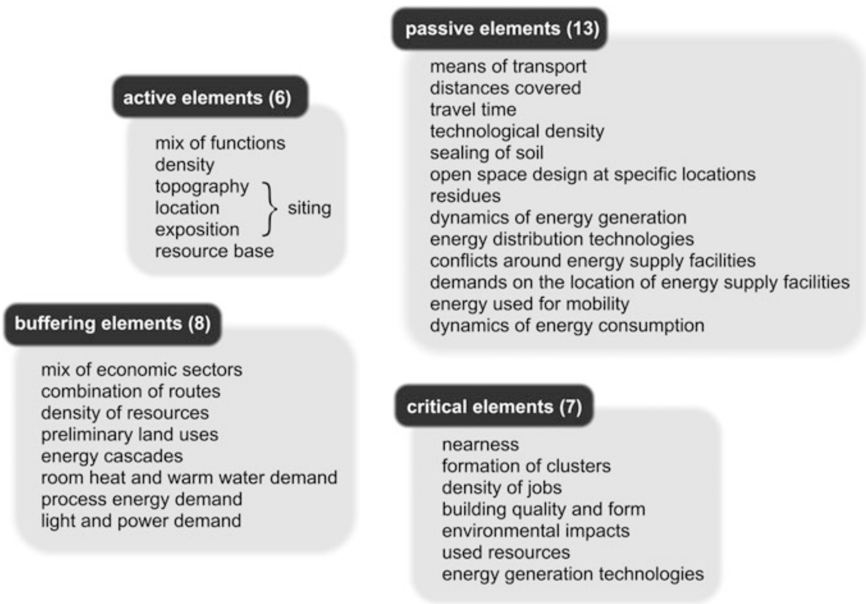


Fig. 2.1 System analysis spatial and energy planning (own illustration after Stoeglehner et al. 2011b)

an analysis, the effectiveness and efficiency of policies, legal frameworks, and plans in supporting the energy turn can be evaluated. The system elements can also be used as criteria to define energy-optimized urban development projects as was already executed in an action research case in an Austrian rural small town, Freistadt (Mandl and Hartl 2011; Stoeglehner et al. 2011b).

Some results concerning the categorization of system elements are rather obvious, whereas other classifications surprised. It has to be considered that the system boundaries are relatively wide and take both spatial and energy planning matters into account. According to the definition of systems laid out before, different system boundaries will very likely lead to different judgments. The analysis of this holistic system shows, inter alia, why some sectorial policies turn out to be very effective, while others fail. Such interpretations can be done because such a crosscutting approach reveals interrelations of phenomena that would be overseen by sectorial approaches. The most important results will be discussed in the next sections.

2.1 Energy Efficiency and Spatial Structures

Our work revealed that besides technological energy efficiency and energy efficiency of lifestyles and economic practices, we can identify a further category of energy efficiency: "spatial energy efficiency" (Stoeglehner et al. 2014b). The concept of "spatial energy efficiency" takes a holistic view on energy demand considering demand for room heating and warm water, mobility, and maintenance of public infrastructures as well as embodied energy in buildings and infrastructures of built environment. Spatial energy efficiency targets the overall energy requirement, excluding only the energy consumed by industry (and agriculture if applicable) in a certain settlement. Figure 2.2 (Stoeglehner et al. 2014a) shows the interrelations for energy demand and supply for residential areas. This section will outline which elements of the spatial energy planning system offer good leverage for system change in favor of the energy turn and why.

System analysis confirmed that regarding energy efficiency a mix of spatial functions, density, and siting are the three most important features for spatial energy efficiency on a macroscale of spatial development. Given a certain structure or energy provision technology, the same supply facilities will lead to a higher overall energy efficiency if they are located in multi-functional, appropriately dense spatial contexts. As a guiding principle, sites for new developments have to be chosen according to these features. This is true both for greenfield and brownfield developments.

Multi-functional, appropriately dense settlements allow for an efficient use of grid-bound energy infrastructure for reasons explained below in detail. Density is a measure of spatial efficiency and includes area values such as population density, density of workplaces, which also lead to increased technical densities, e.g., heat density, which makes energy distribution grid operation more efficient. From a

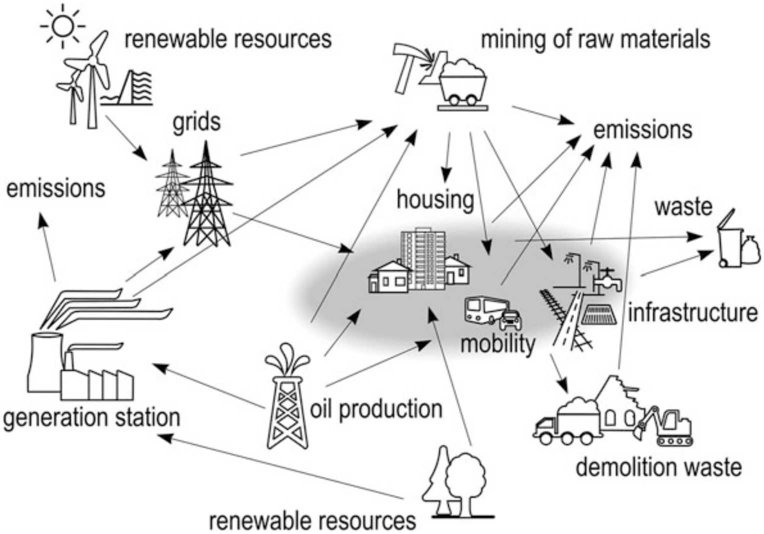


Fig. 2.2 Energy aspects of residential settlements (own illustration after Stoeglehner et al. 2014a)

mere technical-economic point of view, it would be reasonable to postulate that denser spatial structures might be better as long as the building efforts and costs do not exceed the optimum because of too intricate building measures.

This applies not only to construction and maintenance, but density also minimizes the embodied energy in the built structures. Embodied energy is an underestimated factor in spatial development. Evidence from case studies suggests that especially in low-dense residential areas with single-family houses the share of embodied energy in the technical infrastructure (roads, sewer system, water supply) can amount to 55 % of the total energy demand of a settlement, being responsible for up to 90 % of the settlements CO_2 lifecycle emissions. The share of mobility is low, because in low-dense settlements a small amount of persons is living. If state-of-the-art construction techniques for houses are applied, the energy demand for room heat is low. Also the share of house construction is relatively low—normally 5–10 % of the settlement's energy balance when discounted over the life span of buildings. This can make construction and operation of infrastructure the biggest energy consumer in residential areas, which can be easily reduced by denser building schemes. If the same amount of persons is located in three-to-five-story apartment buildings, the share of embodied energy in infrastructure decreases to 5–10 % of the total energy balance, and the share of embodied energy in buildings is likely below 5 % of the total energy balance. If density is higher, the share of energy demand directly related to infrastructure and embodied energy decreases, whereas the demand related to energy services for inhabitants such as mobility and residential heating increases (Stoeglehner et al. 2011a).

Yet, there are limits for density as means to achieve energy efficiency: Settlements can get too dense. Actually, there are two dimensions to these limits, technical and social. In principle, medium-dense spatial structures are more energy efficient than low-dense structures. Technical limits for energy efficiency arise if the energy demand to support buildings reaches a tipping point of too much density and becomes higher again on a per inhabitant basis as for less dense systems. This can happen for extreme high-rise buildings that require considerable energy for operation as well as for construction (embodied energy). Social problems resulting from high density constitute the other dimension of limitation. This may motivate people who can afford it either to move to other places or to look for a second home. For an Austrian small town, it was found out that new medium-dense residential developments, such as row houses, led to a decrease of density in the town as most of the row house dwellers (about 80 %) moved out from high-rise buildings in the same town, fleeing from too cramped living conditions (Emrich Consulting n.y.). Furthermore, people might look for second homes in the countryside. Therefore, infrastructures such as energy, waste, and wastewater treatment in the areas with a high amount of second homes are heavily underused and run on high costs. Furthermore, people traveling from the urban centers to their rural retreats induce increased mobility, mostly by individual car transport.

As a side effect, real estate values decrease in too dense areas, especially when open space is not sufficiently considered in designing an appropriate mix of functions. In Vienna may be observed that in some very dense areas lacking open space the amount of people with low incomes and a migration background is significantly higher than in areas with lower densities and better access to open spaces (Aigner 2013), which might even spur gentrification processes. Therefore, the issue of "economy of scale" versus "ecology of scale" is also valid in the context of density: If the density is too low, proper (energy) infrastructures cannot be provided, so it would make sense to ascribe minimum densities to certain spatial developments. If the density is too high, technical infrastructure and embodied energy may become large. On top of that not only negative effects on the quality of life of the population occur, but the induced behavior to compensate for these effects leads to a higher energy demand of society: (1) More energy is needed and biologically productive land consumed for construction and maintenance of additional buildings and infrastructures in new developments or second homes' areas because of people fleeing from their initial surroundings. (2) Additional mobility is generated for recreational purposes, often with individual cars as the least environmentally friendly means of transport. Finally, not only negative impacts on the energy balances of society and the environment can be detected, but also negative social effects through to gentrification processes. Therefore, "ecology of density" has to be taken into account by assigning minimum and maximum densities for spatial developments. These density values should be considered in building schemes in all kinds of land uses. Even from the energy viewpoint, these density values have to be guided not only by energy efficiency issues, but also by quality of life for the population. Low quality of life might lead to increased energy consumption—if the population possesses enough economic power to take remedial action. These actions may lead to massive rebound effects decreasing the overall density of spatial structures when second homes are included and even higher ecological and economic pressures when increased individual car mobility is factored in.

Mix of functions is an important feature for spatial energy efficiency, as it (1) increases the efficiency of energy grid systems, (2) allows for energy cascades, and (3) has an enormous impact on mobility. First, mix of functions very likely increases the amount of full operating hours of an energy grid system. Each spatial function has a characteristic load function on different timescales. For instance, in winter the room heat demand is highest in the morning and evening and on weekends in residential areas. Complementarily, in commercial areas, the room heat demand is highest during the day and low during nights and weekends. If a grid supplies a single-function area, e.g., a residential area, the variation between base load and maximum load is high, whereas the varied load curves in mixed-use areas will dampen these differences with a high probability leading to a more stable overall load curve which in turn will increase efficiency of the energy provision installation. This is due to the fact that all provision technologies run at considerably lower efficiencies when not operated at full capacity. In Austrian climatic conditions and settlement patterns, district heating grids in pure residential areas normally reach 1500–2200 full load hours per year, whereas mixed-use areas normally reach 4500 full load hours per year. If highly energy intensive facilities such as hospitals, spas, indoor swimming pools are served by the grid, full load hours can increase up to 6000 hours per year, leading to considerable increases in energy provision efficiency (Neugebauer et al. 2015).

Energy systems are especially efficient if the spatial structures allow for energy cascades (see Fig. 2.3). Heat sources such as power plants and industrial facilities provide heat at different temperature levels. In many cases, heat sinks also require heat

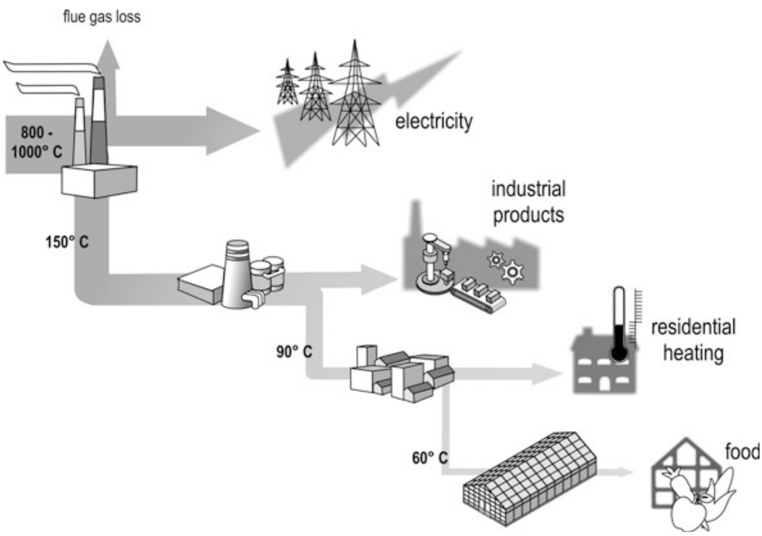


Fig. 2.3 Energy cascade (own illustration)

at different temperature levels. A cascading use of heat now means that from sources to sinks are matched in a way that leads to minimal primary energy input to the whole system. This usually takes the form of using heat that is leaving a certain element in the system to heat another element, so that the heat flow is "cascading" from a high temperature level where it supplies a consumer requiring this high-energy quality to consumers requiring lower heating temperatures (Ayres et al. 1998).

Heat cascades can take very different shapes and depend on the context. An example is a combined heat and power (CHP) plant linked to a district heating system. The heat generated by combustion (depending on the fuel in a temperature range between 800 and 1300 °C) drives a steam turbine, which needs this high temperature to achieve high electricity generation efficiency. The heat of the flue gas leaving the chimney is lost to the environment. The steam leaving the turbine (if it is a back pressure turbine) may be condensed at a temperature level of 150 °C, raising steam to heat an industrial process. Condensing this steam generates heating water at 90 °C that is distributed in a district heating system to residential areas with conventional heating systems. By heating these houses, the water in the grid is cooled to 60 °C, enough to operate low-temperature heating systems in well-insulated state-of-the-art buildings. The water flowing in the grid is further cooled to 40 °C by serving these high-energy standard houses. This temperature may be still high enough to heat greenhouses (Dragone and Rumi 1970) bringing the water temperature in the backflow to the power station to 30 °C (where it is again heated to 90 °C and starts the heating cycle anew).

Heat cascades of course must follow the first law of thermodynamics. It is not the "same" kWh that cascades through all these steps and serves these consumers. The fuel in the CHP plant has to provide the heat for the sum of the demand of all consumers. The only heat loss, however, is the heat lost with the flue gas of the CHP plant. If the CHP plant is replaced by a pure power plant, the heat loss through the flue gas would be comparable, but in addition the heat cooled away by condensing the steam after the turbine is lost as well. It is this heat that serves all the consumers in the cascade and is put to work rather than escaping to the environment. In addition to that, by consciously planning for energy cascades, maximum full load hours considerably exceeding 6000 h can be achieved in grid operation (Lund et al. 2014).

For mobility, a mix of functions is extremely important for environmentally friendly means of transport as well. As structure influences behavior (as well as behavior influences structures) mixed-function, appropriately dense areas spur environmentally friendly means of transport such as walking, biking, and public transport. In such areas, there is no need to use the car, so significantly more daily ways are covered by these means. This can be demonstrated on mobility surveys of municipalities (see, e.g., Stoeglehner et al. 2011a), and mix of functions as a means of reducing travel time and distance is an important claim in many urban planning visions. When we look into greenhouse gas balances of industrialized countries, mobility is a main contributor to climate damaging emissions. In Austria's climate balance emissions from private sectors are decreasing, whereas mobility spoils the balance the most (Umweltbundesamt 2013). Yet, considerable efforts are made in

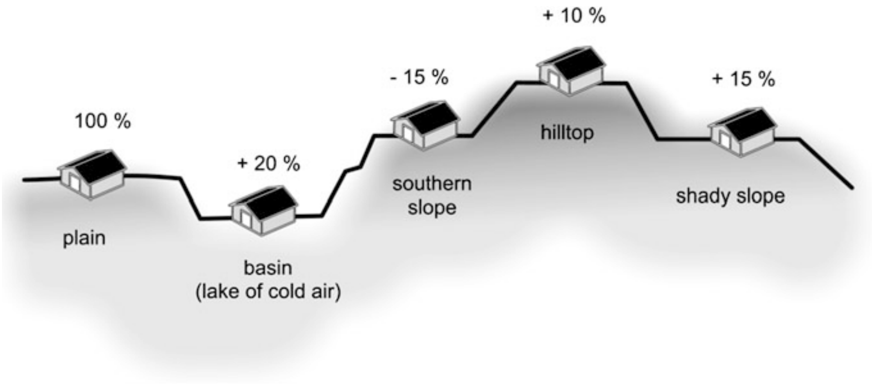


Fig. 2.4 The influence of siting on energy demand (own illustration after EnergieAgentur.NRW 2008; Treberspurg 1999)

the transport sector, but with little effect. Surprisingly, system analysis indicates that mobility is a passive element. Passive elements, however, offer no good leverage for system change. This observation corresponds to the real development, which reveals steady increases of car traffic except for well-organized urban centers and small towns. Simultaneously, spatial development in many regions is dominated by sprawl. This is all the more regrettable as spatial structures are very long lasting.

Furthermore, siting is an important factor for spatial energy efficiency. Not only that siting of new developments—both greenfield and brownfield—decides about the implementation of the mix of functions, but it also takes up the topography and exposition of certain areas. Topography can only be changed on the microscale. On the macroscale, together with exposition it can only be taken into consideration as a boundary condition, which determines, e.g., the amount of direct sunlight and the active and passive use of solar energy. Figure 2.4 shows the influence of siting on the energy demand of residential houses and the relevance for spatial energy efficiency under Central-European climatic conditions. On the microscale, also the design of specific locations has an impact on spatial energy efficiency, but can be influenced rather easily if considered in planning processes: For instance, the shadowing of trees or other buildings can be easily avoided if taken into account in building schemes.

Critical system elements related to spatial structures are nearness, formation of clusters, density of jobs as well as building quality and form. They may also induce system change, but as more rebound effects through more complex cause–effect relationships in the system are to be expected, they have to be treated more carefully. This is especially true when different spatial scales, e.g., regional and local, are taken into consideration. Nearness is on the border between active and critical elements and influences the choice of means of transport, as it has an effect on travel times and distances. Problematic is the subjective character of nearness, as it is highly influenced by individual perception and depending on certain regional and local spatial contexts. Therefore, nearness should be assessed related to travel time budgets instead of distances (Cerwenka et al. 2000). A specifically critical aspect of nearness is the distance between dwelling, work, and daily supply, which also corresponds to the system elements formation of clusters and density of jobs. However, nearness is likely guaranteed in mixed-function areas, especially the abandoning of certain functions on the local scale even if all functions can be still supplied on the regional scale—e.g., in shrinking regions—might decrease nearness to an extent where tipping points are reached: e.g., If nearness between dwelling and work decreases too much, people might migrate instead of commute, which leads to a destabilization of the local population, an increase in second homes and to accelerated spatial development in labor market centers with the respective increase of energy demand concerning embodied energy for additional building efforts.

Clusters are economic agglomerations around one or few thematic areas such as products and/or services, e.g., automotive industry clusters or IT industry clusters. The actors of clusters, such as companies, research institutes, universities, are closely linked with each other (Springer Gabler Verlag n.y.). Clusters have specific influence on accessibility and the energy demand for (industrial) processes. As long as the products and services are demanded on the markets, clusters might provide high economic prosperity for certain regions, but if demand falls, this might cause severe economic crises in the affected regions and a high loss of jobs carving negative development spirals. In contrast, a mix of economic sectors on a regional scale is a buffering system element, stabilizing the system and providing for more opportunities to cope with crises. These interrelations are relevant for the energy systems as they have influence on mobility patterns and their respective energy demand, the energy demand of production processes as well as on the resource base for the regional energy provision, especially concerning energy cascades.

On the microscale, the building quality and form are critical system elements, as they heavily influence the range of energy technologies that can be applied in a certain spatial context. Concerning already-existing built structures, a high-energy demand is due to low energy efficiency of buildings. Taking single-family houses in Austria into account, at a current refurbishment rate of about 1 % of the building stock per year, it takes something around 100 years to adapt existing buildings to contemporary buildings standards (Baumgartner et al. 2010). In newly developed areas, demand from low energy houses can be minimal, and in combination with on-site renewable energy provision technologies, even an energy surplus can be reached. Such developments very likely make, for instance, district heating grids in newly developed or restored areas obsolete. Therefore, the feasibility of grid-bound energy systems has to be regularly re-evaluated. If tipping points by the broad application of energy-efficient building technologies are reached, system change from centralized to decentralized energy provision is likely to happen. As such change has severe economic and environmental consequences, it has to be permanently monitored and taken into consideration while planning visions and measures.

2.2 Renewable Energy Provision and Spatial Structures

To shift from a fossil and nuclear energy provision to a renewable resource base means to increase land demand for energy supplies (see the resource garden metaphor in Chap. 1). Therefore, additional land uses or multiple use of land (e.g., when solar panels are mounted on roofs or wind turbines are erected on pastures) are introduced into already intensively used areas, causing considerable land use change and making land use conflicts very likely. Therefore, an important task for integrated spatial and energy planning will be to search for agreeable locations for renewable energy installations on the one hand and to protect present and future resource provision areas on the other hand (Stoeglehner et al. 2014b).

Existing spatial structures heavily influence the possibilities to introduce energy provision facilities, as can be illustrated by wind energy: Wind energy impacts, compared to other energy provision technologies, relatively few environmental issues negatively. Except on bird and bat protection and landscape sceneries, the impacts can be resolved by safety distance approaches, e.g., protection from noise and shadowing (Felber and Stoeglehner 2014). Therefore, in order to build wind parks with minimal conflict, spatial structures with huge areas between settlements are needed. Given the fast development of technologies with spin wheels becoming bigger and bigger, even higher distances between wind parks and settlements are needed. This leads to the conclusion that sprawl situations complicate or prevent wind energy use, whereas mixed-function, appropriately dense areas save open space and offer more possibilities for the use of renewable energy sources.

Although our system analysis covers 14 system elements concerning energy supplies, only one system element is evaluated as being active and three as being critical. The active system element is the resource base, which determines the critical system elements technologies and related environmental effects. From a planning point of view, it is therefore more promising to plan the resource mix in the energy supply in planning visions than focusing too early on technologies, although these issues cannot be completely separated. The focus on resources can also help mitigate environmental effects by taking ecological capacity limits in renewable energy provision into account. For instance, the amount of biomass production can be determined on the local and regional scale considering the regional ecosystem limits. Which maximum rates of provision of certain energy sources, may this be biomass, wind or solar energy integrated in buildings, are environmentally feasible and socially accepted can be expressed based on regional energy potential surveys. The determination of capacity limits can take the societal value base into account, expressed, inter alia in the food versus fuel debate, the toleration of landscape change, etc. When the resource base for a renewable energy supply, which can be environmentally feasibly extracted, is defined in a certain spatial context, technology portfolios to make best use of this resource base can be agreed on. In the choice of technologies, socioeconomic issues can be taken into consideration.

On the microscale locating energy generation facilities, their environmental impacts as well as their resources have the character of critical system elements.

The selection of sites as well as the type and size of the plant, which are determined by the resources applied, accounts for possible conflicts about land uses as well as social acceptance. If not enough environmentally and socially feasible sites are available for a certain determined technology option, this poses a considerable threat for master-planned future energy systems that were mainly based on technological and economic analyses. Spatial analysis will make such energy plans even more feasible by considering regional and local conditions, yet it is possible that stakeholder involvement, or even the resistance of the public against a certain element, e.g., a certain energy generation plant, might delay or prevent a desired energy planning option by the respective decision-makers, threatening the applicability of the whole energy action plan. In order to resolve this problem, we dedicate Chap. 6 to planning processes and tools.

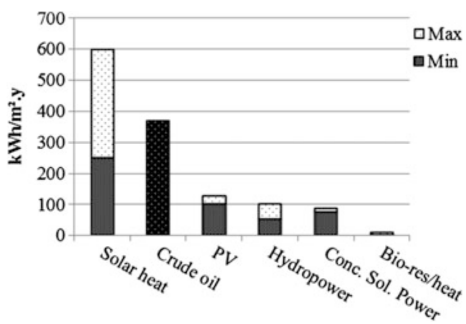
2.3 Energy Logistics and Spatial Structures

Energy logistics is a key problem concerning the technological networks supporting the energy turn, as renewable energy sources have very different characteristics than fossil and nuclear energy sources that have to be replaced. These different characteristics of renewable energy sources strongly relate to the spatial dimensions of the energy turn.

Solar radiation does not provide the same energy density than fossil resources, as they are typically decentral and bound to area in contrast to fossil and nuclear resources that are typically point resources, emerging from a mine or bore hole. Figure 2.5 shows the energy-harvesting density for some renewable energy sources compared to fossil crude oil. This is the energy that may be harvested from one m^2 per year.

Figure 2.5 shows that the energy harvest density in kWh/m^2 year is high for solar heat, even higher than that for crude oil (measured as the annual energy output from a Middle East oil field divided by its area). All other renewable energy forms have distinctly lower energy harvest densities than crude oil. While the harvesting density for solar heat is high, transport of heat is limited as will be discussed below.

Fig. 2.5 Energy-harvesting density for different energy resources (Narodoslawsky 2014)



This makes solar heat an interesting option for settlements to convert solar radiation directly to heat, using the area of roofs. It will compete, however, with PV which shows a significantly lower harvesting density but provides electricity, an energy form of much higher quality. Both PV and hydropower, although with much lower energy-harvesting density than crude oil, may still warrant their utilization in central installations. The energy-harvesting density for biomass is, however, dramatically lower than that of other sources. This is due to the low efficiency of transformation of solar radiation to usable energy of plants. This means that the logistics of collecting biomass is a major challenge and that decentral energy conversion technologies based on biomass have distinctive logistical advantages compared to large centralized units (eseia 2014).

Digging a little deeper into the spatial connotation of the use of bioresources reveals the magnitude of this challenge. Table 2.1 shows humidity, density, and energy density (based on incineration for relatively dry materials and biogas production for wet materials).

This table reveals that energy densities for bioresources differ by an order of magnitude and are in any case considerably lower than those of fossil materials. The logistical challenge becomes even more visible if different means of transportation are factored in. According to their transport efficiency (and strongly influenced by their particular ratio of empty weight to load capacity), different means of transportation require different energy to transport a load over a certain distance. If the limit of the energy used to transport a resource to its utilization site is arbitrarily set to 1 % of the contained energy, the following results are obtained (Narodoslawsky 2014):

Table 2.1 Transport parameters for different bioresources compared to fossil energy carriers (own table after Gwehenberger and Narodoslawsky 2008)

Conversion	Material	Humidity (%w/w)	Energy content (MJ/kg)[a]	Density (kg/m^3)[a]	Energy density (MJ/m^3)[a]
Incineration	Straw (gray)	15	15	100–135	1500–2025
	Wheat (grains)	15	15	670–750	10,050–11,250
	Rape seed	9	24.6	700	17,220
	Wood chips	40	10.4	235	2440
	Split logs (beech)	20	14.7	400–450	5880–6615
	Wood pellets	6	14.4	660	9500
Biogas production	Grass silage	60–70	3.7	600–700	2220–2590
	Corn silage	65–72	4.2	770	3230
	Organic municipal waste	70	2.4	750	1800
	Manure	95	0.7	1000	700
	Light fuel oil	0	42.7	840	36,000
	Anthracite	0	35.3	800–930	28,000–33,000

[a]All numbers are related to fresh material

- In the case of manure, straw, and corn silage, 1 % of the contained energy will power a tractor (as the most common short distance means of transportation on farms) 5, 7, 12, or 18 km, respectively;
- 1 % of the energy contained in wood chips and split logs will power a truck for 40 and 100 km, respectively;
- For wood pellets and corn, a train will go for 475 and 525 km, respectively, using 1 % of the transported energy content;
- An ocean going ship loaded with crude oil, however, will travel 7800 km with 1 % of the energy contained in its cargo.

Low-grade bioresources and biowastes offer major potential as sources for sustainable energy systems as they do not compete with other functions of bioresources such as nutrition or raw materials for timber, pulp, or paper industry. These numbers mean that these bioresources may, however, only be utilized close to the points of their emergence. Making low-grade bioresources transportable over longer distances requires decentralized treatment facilities. Treatment can include different methods: The simplest is drying, such as wood chips to be burned in combined heat and power (CHP) cycles for electricity generation and district heating, or district heating alone. Also sludge from wastewater treatment has, if dried to a water content of 20–30 %, e.g., by solar–thermal energy or by the use of waste heat, a calorific value in a comparable order of magnitude as brown coal (DWA 2012; Böhmer et al. 2001). If dried sludge is processed in mono-incineration plants and the ashes are separately stored, they can be used for phosphor recovery (ÖWAV 2014), so that energy and resource generation can be combined.

When it comes to biomass, the concept of biorefineries is increasingly used to exploit as much resource potential as possible: First, biomass can be transferred to biofuels or platform chemicals, i.e., semi-products that can be used as raw materials for chemical processes, allowing for a non-fossil resource base of the chemical industry (Stoeglehner et al. 2010). Wastes and low grade by-products of biorefineries may then be utilized to generate power and heat. Both the off-heat from process energy of the biorefinery as well as the heat from CHP-based electricity generation can be provided by district heating grids. Generally, CHP systems work more technically and economically efficient the higher the demand for heat is. This is heavily influenced by the spatial structures that can be provided with a district heating system, as already stated above. On the one hand, multi-functional, appropriately dense spatial structures should be aimed for supply areas. On the other hand, a second conclusion about the planning of CHP supply is suggested (eseia 2014): The size of a CHP system should be oriented on the heat demand, so that the available heat can be used by customers, making electricity the by-product. CHP systems trying to maximize electricity output without looking at the usability of the heat side are less energy efficient and have a higher risk to fail economically. In Austria can be observed that due to high biomass prices, electricity-only biogas plants cannot be run with an economic surplus at the moment (E-Control 2014). CHP plants hint at still another spatial aspect of bioenergy technologies: They link different distribution grids. In more general terms, intersections of distribution grids are particularly favorable sites for either biorefineries or bioenergy technologies based on lower grade bioresources. Many bio-based energy technologies provide energy in different forms. CHP plants, regardless if based on incineration or biogas, in general provide electricity and heat. Biogas fermenters may supply CHP plants and upgrading units as well. These upgrading units separate methane that may be injected into the gas grid. The same holds true for synthetic natural gas (SNG) plants that gasify solid bioresources and may again supply CHP plants and methane injection. All these technologies "hybridize" energy systems and may switch between different distribution grids according to the demands for different energy forms.

A second challenge arises from the fact that some renewable energy sources such as solar energy and wind energy show cyclical and intermittent time dependencies in their supply. As PV and wind power are dependent on natural phenomena, and energy demand, however, is following economic and behavioral rules, discrepancies between demand and supply of energy are inevitable. In addition, the electrical grid as the densest distribution grid offers very limited storage capacity, especially for storage of energy over time spans exceeding minutes. Spatiotemporal modeling is an appropriate tool to determine within a certain spatial context, e.g., a settlement, a town: (1) how supply and demand curves correlate; (2) which amount of energy in which time spans can be directly used without delivery to a grid or has to be either stored or requires grid capacity to be transported to other places of demand; or vice versa, (3) during which time periods electricity has to be taken from the grid to cover the demand. A spatiotemporal analysis of photovoltaic (PV) use in a residential settlement under Middle-European climatic conditions and consumer patterns revealed that about 20–40 % of the yearly energy demand can be accommodated in the energy system without a high storage or transportation demand, whereas PV provision levels above 40 % of the yearly energy demand make either storage or grid capacity necessary (Ramirez et al. 2015).

Besides trying to overlap demand and supply by using spatiotemporal analysis, there are other options to overcome the intermittent nature of important renewable energy sources that have profound impacts on spatial structures. Storage is of course an obvious candidate. It is, however, a fact that storage costs are high for electricity, the energy form whose distribution grid has the lowest storage capacity.

Figure 2.6 compares different electricity storage options and shows that using batteries for storage of excess electricity is prohibitively expensive. The figure indicates that a hybridization of grids and the link between grids may hold considerable potential for making energy distribution both smart and stable. Integrating bioresource-derived electricity to stabilize grids is certainly one option, but here decentral CHP plants must cooperate within a smart grid architecture due to the logistical parameters of bioresources discussed above. As mentioned already, the size of CHP plants should be defined by the heat demand, and its operation, however, must follow the demand of the electricity grid. This then leads to the necessity of storing heat as its generation is technically coupled to electricity generation. Heat, however, is easily and cheaply stored, at costs of less than 10 % of the cheapest way to store electricity (Narodoslawsky 2014).

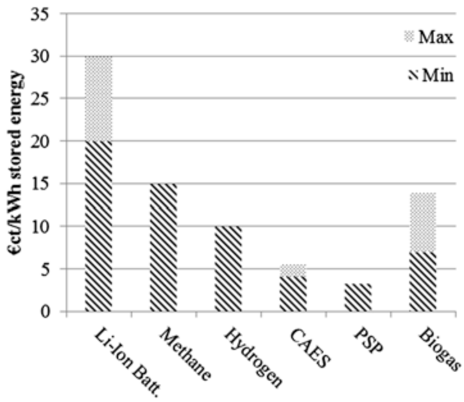


Fig. 2.6 Cost for electricity storage (Narodoslawsky 2014). Methane refers to methane generated by power-to-gas processes, Hydrogen produced by electrolysis, CAES Compressed Air Energy Storage, PSP Pump Storage of Power, Biogas produced from grass silage

Other challenges arise from using excess electricity generated by wind power and PV to produce hydrogen and methane in power-to-gas systems. This calls again for linking the gas and electricity grids and, in the case of methane production, the optimization of siting of conversion plants as they need carbon dioxide from either fossil- or bioresource-based power plants as well as other industries as cement production (Reiter and Lindorfer 2015).

A third major challenge is linked to the different properties of energy distribution systems. They differ widely in their storage capacity and the losses when transporting energy over a certain distance. Assuming the same 1 % of energy loss for transporting (after Narodoslawsky 2014), this will transport the following:

- natural gas via a gas grid at full capacity for 250 km,
- electricity in a high-voltage (380 kV) grid over 100 km and
- in a medium voltage grid (110 kV) over 17 km, and
- heat in a district heating system for less than 1 km.

It is obvious that these numbers again have strong spatial implications. Both high-voltage electricity and gas grids are clearly interregional, even continental in their distribution characteristic. Heat by contrast is distinctly local. Following the argument pursued before, any CHP installations must be sized to serve local heat demand and may use interregional grids to distribute higher value energy or support their stability. Conversely, as a challenge to spatial planning, heat surplus emerging from utilizing regional low-grade bioresources should meet spatial structures that are able to absorb this heat.

Regarding storage capacity, heat and gas grids show high capacity for storing intermittently provided energy. The electricity grid, however, is least tolerant regarding intermittent energy provision. This means that operation of grid-overarching energy provision technologies must be oriented to the needs of the electricity grid while storing energy preferably in the form of heat and gas.

The challenges discussed above are general and apply to rural as well as urban and metropolitan spaces, however, with different emphases. Smart city development in particular must, among other factors, include these considerations about the spatial connotations of low-carbon energy systems. The arguments above, however, reveal that the planning for smart cities does not stop at the city perimeters: resources as well as distribution systems for energy systems require a holistic spatial view that also includes the city hinterland as it has to consider resources and distributions systems in the settlement area itself.

2.4 Energy Resilience and Spatial Structures

In light of upcoming challenges regarding climate change and the energy turn common strategies, concepts, and models concerning spatial planning are getting supplemented with new approaches and terminologies. This also applies to the new concept of resilience and the attempt of developing more resilient spatial structures.

Generally, resilience is a much-discussed concept and is used differently by various disciplines. From an overall perspective, resilience can be described as characteristics of social, environmental, or economic systems comprising the ability to (1) preserve the core functions, structures, and the identity of a system in case of a shock, stress, or disturbance, (2) stabilize disturbed processes after the event within a given period of time, or (3) enable the system to adapt and reorganize (Bourbeau 2013; Birkmann 2008; Holling 1973, 2001; Walker et al. 2004). Therefore, both the duration and the spatial dimensions of the disorder play a decisive role and more or less determine the successful way of handling a crisis (Carpenter et al. 2001).

In order to cope with disturbances, resilience-based planning does not need to focus on missing but on existing system characteristics, such as regional resources, social skills, and adaptive capacity (O'Brien 2009). Furthermore, resilience must be understood as a continuous process not a desired target state, which means an ongoing development toward an often unknown direction. Long periods without crises or stress might lead to routine and may imply a wrong sense of security, stability, or balance. Resilient planning anticipates and accepts changing circumstances and, therefore, attempts to deal with uncertainties in advance (McAslan 2010; Bohle 2007). Only by considering these perpetual processes of change, potential crises can be detected ex ante and the respective system might be prepared for no longer unexpected and convertible challenges. Therefore, resilience thinking includes learning processes about the adaptation of the value base, visions, objectives, and action strategies in light of observed and perceived changes. In the context of integrated spatial and energy planning, resilience, thus, calls for a periodic monitoring and evaluation of spatial development and energy systems and the respective inter-linkages. By providing measures concerning the cognition of future risks, communities are able to preliminarily assess and adjust their visions and have the opportunity to choose between alternative planning options. Therefore, the integration of resilience thinking into current planning system can help to recognize upcoming problems at an early stage in order to consequently identify potential solutions.

Analyzing the current energy system with the concept of resilience in mind, the predominant demand and supply of fossil fuels is conspicuous. Fossils are concentrated in relatively few geographic areas and have to be transported over long distances, which results in a high level of dependence on these energy sources. Due to this focus, the resilience of the energy system to a possible energy crisis is low, which makes the system vulnerable. Herein, vulnerability refers to the exposure, the sensitivity, and the susceptibility to suffer of damage in the case of certain external disturbances (Gallopin 2006). As opposite of vulnerability, the ability to preserve systemic structures and properties during disturbances can be mentioned (Gallopin 2006), which herein is defined as congruent with the first level of resilience (see, definition of resilience).

As energy crises could be a possible trigger for stress and disturbance within energy systems, they have to be further discussed. Basically, an energy crisis can be seen as either a restriction of access to one or several energy source(s) or a physical limitation of an energy source, e.g., by exploitation reaching the capacity limit of a source (see, e.g., Schabbach and Wesselak 2012). Consequently, energy crises can be caused by, e.g., a rise of energy prices, global uncertainties, conflicts between energy exporting and importing states, technical malfunctions, attacks on energy-related infrastructures, or by a decreasing availability of an energy source. Therefore, energy crises concerning fossil fuels such as oil or natural gas would have far-reaching global consequences, such as effects on the nutrition, the mobility sector, or the heat supply. At the same time, spatial structures are getting affected by changes in the energy system and influence the resilience of the energy system.

To give an example, the spatial developments of the past two centuries were characterized by a change in energy sources, especially the transition toward fossils, and the development of new technologies especially in the mobility sector, such as cars. Consequently, compact industrial cities could evolve into sprawling, service-, consumer-, and car-oriented settlements due to the utilization of oil and gas. By implementing renewable energy sources into our energy system, significant adjustments of spatial structures could be expected (Fischer 2014; Sieverts 2012).

We argue that resilience needs to be deliberately implemented in processes of integrated spatial and energy planning in order to improve planning strategies, leading us to the concept of "spatial energy resilience," which we introduce here. This concept expresses the possibilities to increase resilience of energy systems by means of spatial planning. According to the previous definitions, we distinguish six dimensions of spatial energy resilience as depicted in Fig. 2.7 (after Godschalk 2002; Birkmann and Fleischhauer 2009; Beatley 2009; Greiving et al. 2009).

Herein, the principle "ability to learn" builds the overall framework for resilient planning and affects the successful implementation of other principles. Learning is a process and means to acquire new, modified or existing knowledge, behaviors, (social) skills, and abilities (Weber 1977; Wilkesmann 1999). Thus, it is a key to cope with new circumstances (Bower and Hilgard 1983). However, in the case of an energy crisis, it will be necessary not only to learn from past events but also to

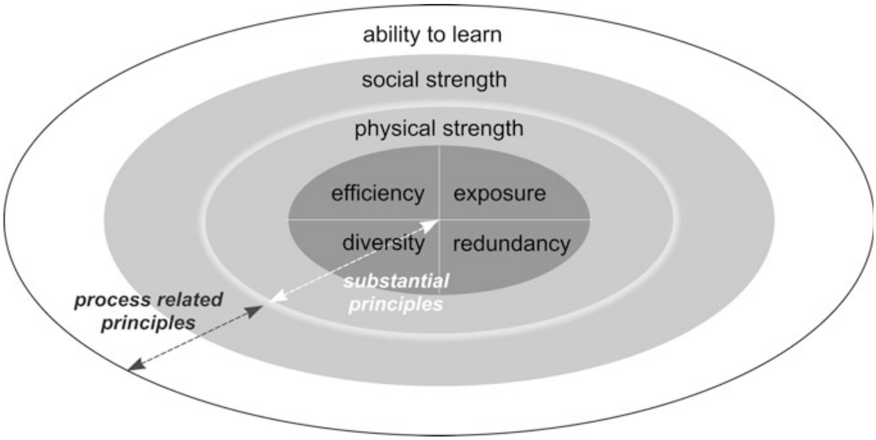


Fig. 2.7 Principles of spatial energy resilience (own illustration)

anticipate future challenges in order to scrutinize and adapt paradigms and own opinions. Therefore, the ability to learn in all its dimensions is fundamental in order to increase resilience. Integrated spatial and energy planning is able to support this principle by creating and preparing fundamental information for decision-making in order to reinforce knowledge, to sharpen the focus of planning debate, and to consider different solutions.

Following this principle, "strength" constitutes a further framework condition and constitutes the link between the overall framework and the remaining structural principles. The overarching aim of this principle is to increase robustness and resistance of existing and planned structures and, thus, to reduce the negative consequences of crises. Strength thereby means the ability of a system to compensate or prevent dysfunction (Norris et al. 2008). In the context of spatial energy resilience, strength has a physical and a social dimension. Herein, the physical dimension refers to the substantial principles, whereas the social aspect of strength is related to the process-oriented principle "ability to learn."

Concerning the physical dimension, characteristics, which lead to spatial energy efficiency as well as to better spatial preconditions for renewable energy supplies and energy logistics, also improve the resilience against energy crises. Therefore, the considerations of the preceding subchapters support physical strength and have to be implemented in accordance with the central principles.

In addition, the social dimension of strength can be identified as properties which increase cohesion and cooperation. This refers to the concept of "social capital," which describes the relationships between individuals, social groups, organizations, or different hierarchical levels (Bourdieu 1986; Coleman 1988; Putnam 1993). Therefore, it is important to support and balance three kinds of relationships: bonding, bridging, and linking. In this context, bonding refers to the like-mindedness of homogeneous individuals and groups. Bridging characterizes the openness to other social structures and values and, therefore, tends to connect people across various social groups. Finally, the term linking expresses the vertical relations between different hierarchical levels (Coleman 1988; OECD 2002; Woolcock and Sweetser 2002). Social capital can be activated by providing facilities where people get the chance to meet and to communicate with each other. In this regard, the revitalization and supply of public spaces, the promotion of civic engagement as well as a strengthened sense of community through a strong club structure need to be supported in order to raise social capital and cope with crises (OECD 2004; Putnam 2001; Bohle 2005).

Depending on how these framework conditions are fulfilled, the substantial principles can be implemented: efficiency, exposure, diversity, and redundancy. As "efficiency" means optimizing the ratio of effort and result, in the context of spatial energy resilience it refers to possibilities to save resources. This complies with the concept of energy-efficient spatial structures as introduced in Sect. 2.1. Despite this positive effect of efficiency, it can also be interpreted as economic strategy to reduce effort to a minimum, which means to provide each function only once in the cheapest possible way—which also would mean at the lowest possible, but still sufficient quality. Therefore, it is discussed if efficiency is a concurring concept to resilience (Löhr 2009). We argue that efficiency interpreted as means to save natural resources is part of resilience, but cannot be separated from the other issues such as diversity and redundancy. Efficiency as part of resilience means that diverse and redundant subsystems are present, but that each of them is also efficient in order to save as much resources as possible and, therefore, also to reduce the ecological footprint of spatial structures and energy systems to a minimum.

This principle is followed by "exposure," which means to reduce the spatial dispersion of settlement structures and infrastructure as well as to minimize the dependencies on energy sources. Self-sufficiency, a reduction of resource and energy consumption and the focus on regional resources in order to guarantee autonomy and independency, can be summarized under this principle.

"Diversity" stands for the promotion of a mixture of different spatial functions and a wide range of energy sources at different locations. The different realizations and unequal design of systems or components provide a broad range of sensitivity to a given disorder. Therefore, some components or systemic parts might stop working under shock while others remain functioning. Diversity promotes the flexibility of a system and gives the opportunity to switch between heterogeneous components. This might lead to a variety of multiple approaches, possible solutions, and opens up room for maneuver.

Finally, the set of principles of resilience in the context of integrated spatial and energy planning is getting completed by "redundancy." In order to support this principle, a number of functionally same or similar components must be created. This increases the systemic security in the event of a crisis. In the case of system failure, the additionally installed component can allow proper functioning. In addition, redundant systems should be installed at different locations in order to minimize the risk of a common vulnerability. In the context of resilient spatial and energy planning, redundancy means to implement structures as well as to enable multiple uses of structures. Herein, this principle must be seen as complementary rather than competing with efficiency, exposure, and diversity. Although similarly functioning components, such as power generation and power distribution systems, can be designed in an efficient way, their intended function has to be covered several times. Decentralized energy systems might be of special value for redundancy, since they tend to increase the resilience by replacing large power plants with a multitude of small energy producers (Stelter 2009). Therefore, the balance of the substantial principles is essential and has to be adequately implemented according to the particular spatial context, as will be pointed out in Chap. 3.

By considering these six principles of resilience, the persistence, adaptability, and transformability of systems might be ensured and, therefore, the quality of planning processes can be improved. The concept of spatial energy resilience must be seen in addition to the considerations of the former subchapters, as they focus on structural and contextual aspects of integrated spatial and energy planning. Spatial energy resilience includes process-related components and connects them with the content level. Therefore, the active system elements should be brought in line with the objectives of resilience. The spatial- and energy-related elements "mix of functions," "density," "siting," and "resource base" can operationalize the substantial principles of resilience: "physical strength" including "efficiency," "redundancy," "diversity," and "exposure." Implementing these system elements could be supported by the process-oriented resilience principles "social strength" and "ability to learn."

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