Disruptive Technologies to Decarbonize Building Energy Systems

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Abstract:

Innovation in the field of technical building equipment is a decisive pre-condition for achieving a virtually climate-neutral building stock by 2050. This work aims to characterize, identify, and qualitatively assess potentially disruptive technologies that are particularly promising for this transition phase. Initially, existing theories on innovation, disruption and sociotechnical transition are reviewed. Based on this, a key criterion for potentially disruptive technologies is suggested: they have the potential to significantly and rapidly increase customer value under current policy and market conditions.

The main causalities between current megatrends, stakeholders, performance criteria and energy technologies that might foster disruption in building energy systems (BES) are determined. Megatrends are amongst else the digital revolution, decarbonization, customization, urbanization, demographic change, resource scarcity and participation. The main stakeholders include building owners and users, energy suppliers, policy makers, entrepreneurs, engineers, craftsmen, and the public. The main performance criteria in BES are the meeting of comfort requirements within the building, safety, economic performance, security of energy supply, and low CO_2 emissions.

According to the above-mentioned criteria, strategies for disruptive technologies are derived. Three emerging technology groups are identified as potentially disruptive in BES: a) flexible electricity-to-heat conversion devices, specifically heat pumps, b) electricity storage technologies, e.g. high-temperature thermal storages and batteries, and c) additive manufacturing of building parts or BES components.

Keywords: Disruptive technology, technical building equipment, heat pumps, additive manufacturing

1 Decarbonizing Energy Technologies for Buildings

Buildings and their energy supply account for about 34 % of the final energy demand in Germany and contribute about 30 % to their overall CO_2 emissions (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), 2019). The German government aims at achieving a virtually climate neutral building sector by 2050 (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), 2016). For a substantial reduction of greenhouse gas emissions of buildings, besides energy-focused refurbishment measures also a massive reduction of the specific CO_2 emissions of the remaining energy demand is necessary.

Technology and business model innovations as well as social factors, trends and regulatory measures will have a great impact on the future energy supply of buildings. Various studies show that the achievement of our climate goals by 2050 is possible (Henning and Palzer, 2013). However, massive efforts and immediate action by all stakeholders are necessary (Ausfelder et al., 2017, p. 14). Within this work, Building Energy Systems (BES) are defined as systems that contribute to the energy consumption of buildings and therefore include the technical building equipment as well as the energy supply technologies of buildings. Will there be disruptive technological innovations in BES that speed up the transition? Might such innovations even be a pre-condition to achieve the climate goals at all? By applying theories on sociotechnical transition and disruptive innovation, this paper aims to characterize, identify, and qualitatively assess potentially disruptive technologies in building energy systems, which are particularly promising on the way towards 2050.

2 Innovation, Transition and Disruption

As a basis for identifying potentially disruptive technologies for the transition of BES until 2050, the term innovation is distinguished from disruption. This is followed by a description of transitional processes and the definition of key features of disruptive technologies.

2.1 Innovation vs. Disruption

Innovation is commonly defined as the development of new ideas for economical purposes (Myers and Marquis, 1969, p. 1; Grübler and Wilson, 2014, p. 7). This can either be achieved through new technologies, new business models or a combination of both. Innovation results in new products or services that are successfully diffused into markets. Innovation can be driven by the availability of new technologies (*technology-push*), which may result in a cost reduction, or by an increased payoff due to market demand (*market-pull*). A very common model to describe technological evolution as the result of innovation is the S-curve model which was introduced by Foster (1985) and is shown in Figure 1.

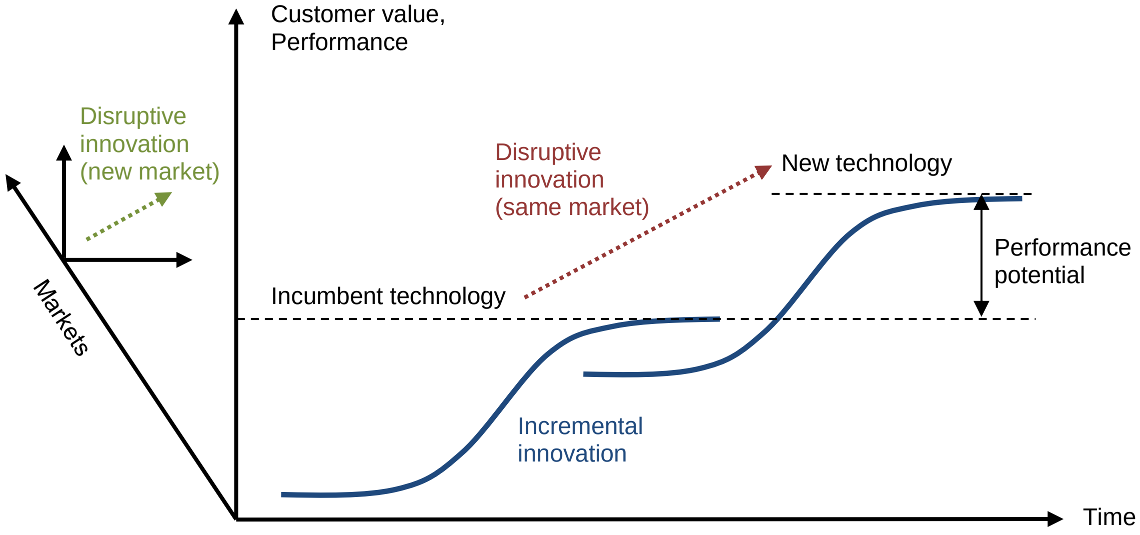

Figure 1: Extended S-curve model distinguishing incremental and disruptive types of innovation adapted from Fuchs and Golenhofen (2019)

The S-curve model sketches the performance of a technology over time. Performance is usually not a single parameter, but “a set of customer requirements that are key buying factors in the business” according to Fuchs and Golenhofen (2019). Instead of performance, these authors favor using the term *customer value* – which is defined as the ratio of performance (fulfillment of customer requirements) and costs (the amount a customer is willing to pay). Successful innovations increase customer value. With this definition, not only a performance increase will lead to better customer value, but also cost decreases. The rate of incremental innovation during the life cycle of a technology is rather low at the beginning and will increase before slowing down towards saturation.

Disruption (or disruptive change) is subject of intense research and discussion. There are a number of theories that differ widely in terms of definition, methodology and use case. The term *disruptive technology* was introduced by Bower and Christensen (1995) and describes technologies that have an initially low performance and address only a small customer segment. Due to a rapid increase in performance they disrupt the market, because incumbent technologies cannot adapt quickly enough or may be in the saturation range of the S-curve.

A technology can be disrupted by a different one, which is shown in Figure 1 as *same market* disruption. This type of disruption can have a high impact on technology stock or certain stakeholders, but will not change the market fundamentally. *New market* disruption includes innovations, that create a market for themselves (Bower and Christensen, 1995; Fuchs and Golenhofen, 2019, pp. 21–23). This meets the definition of Danneels (2004), who states that it changes “the bases of competition by changing the performance metrics along which firms compete.” The impact of new market disruption is higher, but harder to quantify.

2.2 Innovation Techniques

Scientists, engineers and entrepreneurs have come up with multiple strategies to intentionally trigger innovation and to systemize the innovation process. A particular noteworthy set of strategies called TRIZ was developed by Altshuller (2000) based on observations of how technologies evolve over time and an extensive analysis of patents over more than five decades. Key technological strategies to foster innovation include *increasing the degree of ideality* by increasing technological performance and reducing costs, *increasing flexibility*, which enhances functionality and the adoption to changing markets dynamics, *miniaturization,* and *shortening the energy flow path*, e.g. by introducing more efficient steps of energy conversion or eliminating them. Another strategy is the *transition to a higher level system* by increasing functionality and complexity, enabling systems to solve problems that cannot be solved at a subsystem level (National Research Council, 2009, p. 23).

2.3 Disruption as a Transitional Process

Transition models help to investigate the conditions that impact sociotechnical change. Particularly noteworthy is the so called Multi-Level Perspective (MLP) shown in Figure 2 (Geels, 2002), which distinguishes three different transition levels depending on their time scales.

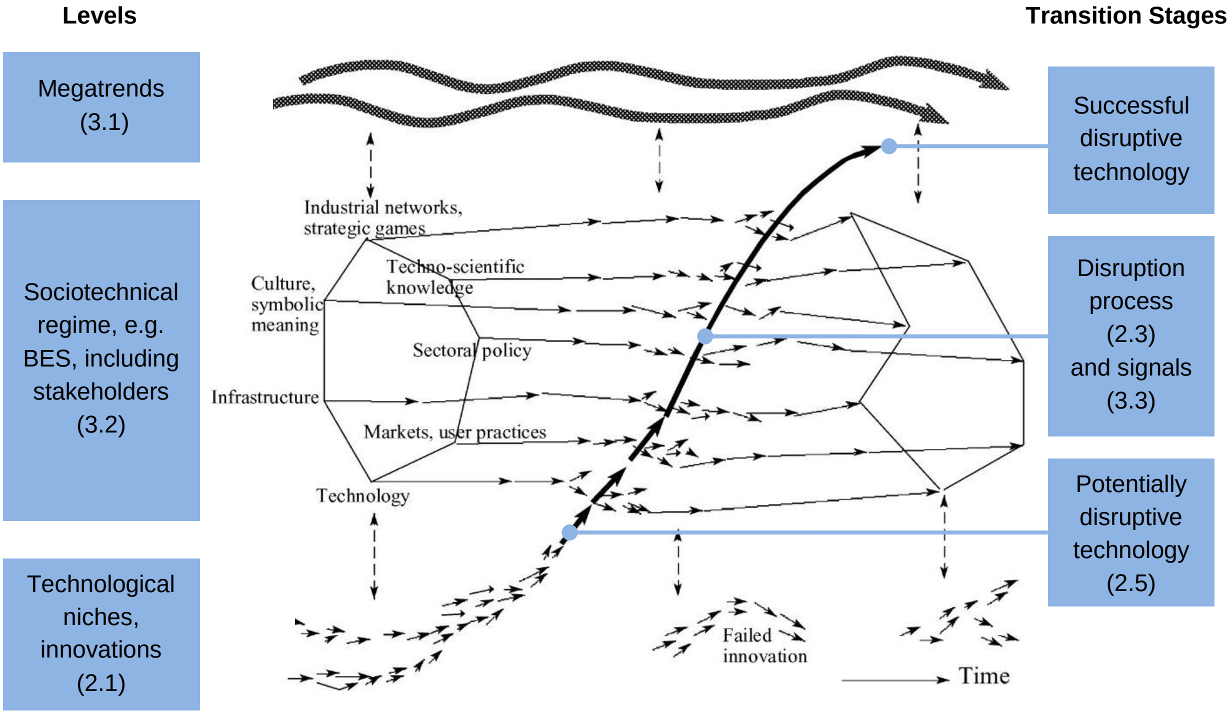

Figure 2: Multi-level perspective on sociotechnical transition (Geels, 2002) as a framework for this work

At the lowest level, new innovations are tested in technological niches (cp. section 2.1). The vast majority of innovations fail and do not leave this level. The second level is the sociotechnical regime, where stakeholders act in different fields of action, e.g. markets, industry, science, policy, technology and culture. The BES as sociotechnical regime is analyzed in 3.2. A *window of opportunity* may open for innovations to succeed. Megatrends, which include long-term cultural, economic and political patterns and are discussed in section 3.1, have an impact on the sociotechnical regime and vice versa.

Disruption can have multiple triggers. A disruptive technology can be such a trigger. Other triggers include new business models, policies or external events as shown in Figure 3. Disruption needs the right setting of all these factors. Policy actions and events take place in the sociotechnical regime.

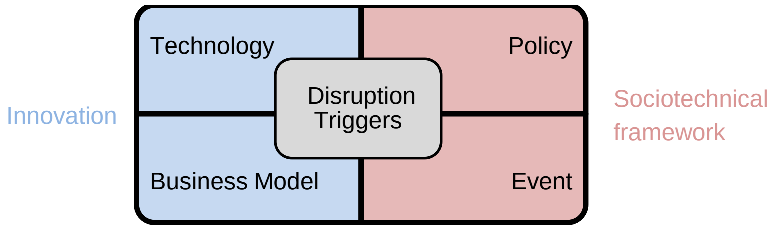

Figure 3: Classification of disruption triggers

To avoid circular definitions as described by Sood and Tellis (2005), this work aims to distinguish between the way disruption is achieved, the transitional process itself, and disruptive technologies that might potentially foster this transition. It considers **disruption** as *a* ***rapid transitional process, which has significant and long-term impact on stakeholders, technology stock and trends.*** This is often the case if the transition is unforeseen by many stakeholders.

2.4 Features of Disruptive Technologies

This work defines **disruptive technologies** as technologies, which ***significantly and rapidly increase customer value under current policy and market conditions*.** This definition presupposes that key customer requirements are met. Furthermore, the following attributes increase the impact of disruptive technologies:

- *Addressing performance criteria and requirements that are new or currently being neglected.* The negligence of customer requirements can decrease the disruption time scale, since incumbent technologies may fail to adapt quickly. This includes competing with technologies that are currently over-performing (Bower and Christensen, 1995).
- *Being scalable in customer value.* This can be either due to an increase in technological performance potential as shown in Figure 1 or due to a high cost reduction potential (Fuchs and Golenhofen, 2019; Sood and Tellis, 2005).
- *Redistributing added value between stakeholders.* This heavily impacts value chains and may thus disrupt certain stakeholders or even create new markets.
- *Addressing current megatrends.* This makes the technology more likely to be in the frame of key stakeholder performance criteria, which are shaped by megatrends.
- *Being applicable across several industries.* This increases the impact of a technology, its benefit from economies of scale and the chances of succeeding.

Disruptive technologies can be classified according to the way of their impact, which is helpful in developing disruptive technology strategies (National Research Council, 2009): *Enablers* make new technologies, processes, or applications possible. *Catalysts* alter the rate of improvement of a technological development. *Morphers* can be combined with another technology to create new technologies. *Enhancers* modify existing technologies to cross a critical threshold in customer value. *Superseders* obsolete an existing technology, replacing it with a superior technology, which has a higher technological potential (Foster, 1985), and *Breakthroughs* are discoveries that change the understanding of nature fundamentally.

2.5 Identification of Potentially Disruptive Technologies

The disruptive potential of technologies and innovations can be assessed by quantitative and qualitative methods (Gallagher *et al.*, 2006, p. 210; National Research Council, 2009, pp. 92–104; Cheng *et al.*, 2017). Quantitative indicators are public and private R&D spending, start-up investments, as well as the number scientific publications and patents. Moreover, S-curves and learning rates (regression analysis) can be determined to quantify and forecast the customer value and performance of technologies and assess their current status. Qualitative methods include surveys or case studies.

3 Trends, Stakeholders and Performance Criteria in BES

Since disruptive technologies are often a consequence of neglected customer requirements, it is important to understand the interests of stakeholders in BES as well as the trends shaping those interests. Section 3.1 describes the relevant megatrends, while sections 3.2 and 3.3 analyze stakeholders, their performance criteria and which factors in the sociotechnical environment of BES are likely to create an opportunity for disruption (cp. Figure 2).

3.1 Megatrends

To gain further understanding on how BES might look like in 2050 and which performance criteria are going to be valued by stakeholders, a proper understanding of so-called megatrends is necessary. A megatrend is commonly defined as a trend that takes place rather slowly over a long period but leads to significant and long-term changes in the fields of the sociotechnical regime. Megatrends are not limited to a region but take place eventually in every region of the world. Megatrends that will particularly impact BES are listed below (Seyler, 2020, pp. 5–12) and is shown in Figure 4.

- *Digital revolution*, which includes changes triggered by digital technology, driven by high computing resources, data connections and the miniaturization of sensors and processors, enabling physical objects to communicate and interact with their environment.
- *Climate change*, as a result of the high level of man-made greenhouse gas emissions.
- *Decarbonization*, as a result of a growing awareness in society for climate protection.
- *Resource scarcity*, especially of non-renewable resources as fossil fuels and minerals, due to wealth and population growth and hence an increasing industrial demand.
- *Customization* includes the higher demand for flexibility in a wide range of applications due to increased market dynamics and the growing desire for individuality – especially of young people – which plays an increasing role in the design of products and services.
- *Urbanization* as the spread of urbanized forms of living. More specifically, it describes the increasing share of people living in urban districts. Forecasts expect nearly 70 percent of the world's population will be living in an urbanized environment in 2050 (United Nations, 2017).
- *Participation (democratization)* is the inclusion of stakeholders, especially the public, in activities and decision making of an organization or system, e.g. in policy making.
- *Demographic change*, especially population growth and increasing living standards in developing countries as well as aging societies in developed countries. High living standards lead to increasing individualism.

3.2 Stakeholders and their Performance Criteria

To understand how potentially disruptive technologies might affect BES and vice versa, an understanding of the causalities between performance criteria, technical parameters, value chains and stakeholders as well as external effects is necessary. In BES, these include – amongst others – building owners and users, energy suppliers, policy makers, entrepreneurs, engineers, craftsmen, and the public.

The main performance criteria in BES are the meeting of physical comfort requirements within the building (temperature, humidity, noise, glare, draft, etc.), economic performance (invest and operational costs), security of energy supply, low CO_2 emissions, reliability, safety, simplicity and an innovative product design (status). Table 1 gives an overview of relevant stakeholders and on the performance criteria especially relevant for them.

This overview reveals amongst else, that only the general public and policy makers – whose interests are largely determined by the general public – see low CO_2 emissions as a key performance criterion, at least as long as these are not linked to an increase in costs. A key stakeholder is the user of BES, since almost the whole range of performance criteria given have an influence on her / his decisions. Soft criteria, as an innovative product design, appeal to customers that value social status. Craftsmen implement the technologies provided by entrepreneurs and manufacturers. They play an important role by advising owners and users. New technologies seem unlikely to succeed, if craftsmen oppose them (e.g. because they are difficult to install or to service). Technological performance criteria (e.g. energy efficiency, capacity, etc.) have an indirect effect on stakeholders and are therefore not included in the table as an independent performance criterion.

Table 1: Stakeholders and their key performance criteria in BES

Performance criteria **Stakeholder**	Costs	Comfort	CO_2 emissions	Supply security	Reliability / Durability	Safety	Simplicity of installation	Design / Status
Owner	x			(x)		x		
User	x	x	(x)	x	x	x	x	x
Energy supplier	x			x	x	x	x	
Policy maker			x	x		x		
Entrepreneur	x							x
Engineer/Manufacturer	x	(x)		(x)	x	x		x
Craftsmen					(x)	x	x	
Public			x	x		x		

3.3 Current Market Signals for Disruption in BES

Typical signals for disruption can be qualitatively derived from analyzing current causalities in BES, including stakeholder’s performance criteria and megatrends. This section outlines market signals that suggest that BES are prone to being disrupted.

Renewable energy (RE) technologies, as wind and photovoltaics (PV), can provide energy at low cost and with low CO_2 emissions (Fraunhofer ISE, 2015, p. 6). The urge for low CO_2 emissions becomes increasingly important against the background of the megatrends climate change and decarbonization, creating a strong market pull for low-emission technologies. Moreover, RE like PV can change market metrics, since consumers can become providers (“prosumers”). Due to their fluctuating nature, they may lead to grid instabilities. Technologies that enable a high share of RE in the grid by providing or consuming energy in a flexible way will therefore increase in customer value for stakeholders.

Energy suppliers still profit from old business models and the current regulatory framework. They are therefore often considered averse to innovation. They do not primarily focus on reducing CO_2 emissions, but on profit and providing power reliably. Hence, their investment in RE is often limited (Lozano and Reid, 2018). The introduction of a CO_2 tax links CO_2 emissions to the economic performance and therefore boost low-emission technologies. In consequence, energy suppliers and technology providers would have to focus on RE and other sustainable technologies. This again would contribute to the goals of society and policy makers to cut CO_2 emissions.

The energy system in Germany is highly regulated. Taxes and levies largely determine German electricity prices. Energy storage options develop at a faster pace than regulations adapt. This can lead to double taxations and hence negatively impact the economic competitiveness of storage options. Highly regulated markets are typically prone to be disrupted by new policies that may remove barriers for new technologies.

Climate change will increase the frequency and severity of extreme weather events (Wiseman, 2018), as e.g. the Australian bushfires 2019/20. Public movements, as e.g. Fridays for Future, are gaining momentum and putting pressure on policy makers. New policies may be implemented rapidly if the public pressure is high, as has been shown e.g. by the German phase-out of nuclear power in the aftermath of the Fukushima incident 2011.

4 Strategies and Examples of Disruptive Technologies for BES

This chapter examines historic examples for disruption, suggests strategies to foster the development of disruptive technologies today and exemplarily describes three promising technology groups for BES.

4.1 Historic Examples of Disruption in BES

Analyzing historic examples of disruption is useful to get an understanding of disruptive change and the influencing factors. This section exemplarily examines the development of the electricity supply and the market uptake of photovoltaics.

Electricity supply to households can be considered as a disruptive technology. It was mainly initiated by lighting. The incumbent lighting technologies – gas and oil lighting – often led to fires and soot formation. Electric lighting replaced these technologies by providing cheaper and better quality services and meeting safety requirements that were not met before (Fouquet, 2016). Two technologies enabled this development: firstly, the discovery of the dynamoelectric principle, which enabled the generation of electric energy, and secondly the invention of the electric light bulb itself (breakthrough). These technologies themselves disruptive technologies (enablers). Electrification, originally initiated by innovations in lighting technologies, not only became disruptive for existing technologies but created new markets. Electricity supply enabled the advance of new household devices and created new customer needs. A thorough description of the historic development of the electricity supply and the interacting technological and market forces is given by David and Bunn (1988).

The fast market uptake of Photovoltaics (PV) as a new technological concept and alternative to existing technologies based on fossil fuels was disruptive as well. It changed the market fundamentally as energy consumers became energy producers and the share of fluctuating energy sources in the grid increased. The economic efficiency in Germany was at first given due to subsidies (German Renewable Energy Sources Act, EEG). In terms of the performance-cost-ratio, PV has gone through a classic cost learning curve, which has led to a better economic performance and has enabled policy makers to cut subsidies on this technology (Fraunhofer ISE, 2015). PV influences a wide range of actors (e.g. manufacturers, energy suppliers, owners) and sectors (e.g. energy, construction, automotive) and advances the decarbonization of BES. The success of energy system technologies in the past strongly depended on fossil fuel prices and political events. This was decoupled by local primary energy production with PV. Installed power has increased exponentially in the last three decades and is projected to grow continually until 2050 (Masson and Kaizuka, 2018).

4.2 Technological Strategies to Promote Disruption

In Figure 4 a set of strategies to foster disruption of technologies is derived. These strategies are based on a qualitative analysis of megatrends, stakeholder performance criteria and disruption signals in BES as described in chapter 3, as well as on a general understanding of the nature of disruptive technologies and innovation techniques as described in chapter 2.

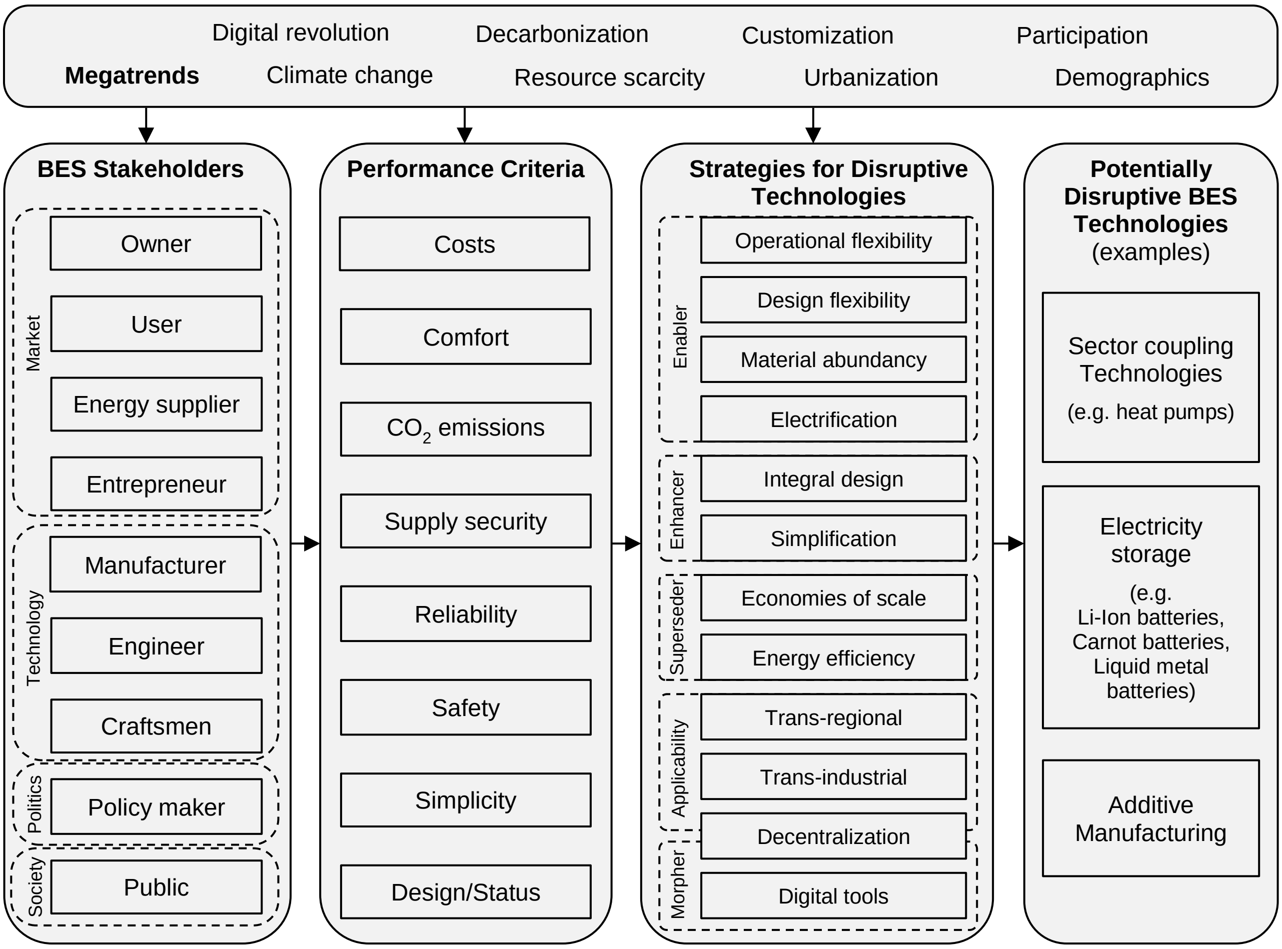

Figure 4: Overview of strategies for disruptive technologies in BES

According to the principle of *transition to a higher level system*, which states that technical challenges may be solved on a higher level if a solution at component level is not possible, BES which include energy supply are addressed rather than only technical building equipment.

Key strategies to decarbonize BES by enabling high shares of RE in the grid include operational flexibility and electrification. Flexibility addresses the need of stakeholders to adapt to increased market dynamics and is another commonly observed pattern in technological innovation. Design flexibility focusses on the need of increased customization.

Choosing earth-abundant materials addresses resource scarcity. It can be economically beneficial and may reduce the dependency on imports, which are subject to political influence (cp. the ongoing trade conflict between the USA and China since 2016).

Another strategy group focusses on disrupting technologies by crossing critical thresholds in customer value. This includes methods of integral design (miniaturization) and simplification. Integral architectures are common when new technologies arise and may trim those to achieve a higher performance. However, once they overshoot minimal customer requirements, they are prone to be disrupted by modular architectures (Fuchs and Golenhofen, 2019, p. 54). Technical building equipment that can easily be installed benefits craftsmen and therefore decreases barriers for widespread adoption.

Furthermore, economies of scale may lead to a rapid scaling in customer value and the crossing of critical thresholds. These approaches are based on literature on innovation strategies (National Research Council, 2009; Yu and Hang, 2011; Fuchs and Golenhofen, 2019). Economies of scale can lead to cost reductions due to either highly automated production lines that produce high output and therefore decrease the cost per unit or large-scale solutions that decrease the specific costs (e.g. power plants). The development of energy-efficient technologies has been included in the set of strategies, as it is crucial for decarbonizing BES and has been postulated as key innovation technique in section 2.2. Other technological parameters strongly depend strongly on the chosen technology and are therefore not included within this set of strategies.

Design for applicability in several regions and industries aims at increasing the impact of a technology. This includes addressing niche markets firstly and then switching to large markets. Decentralization – e.g. in energy supply and manufacturing – can heavily impact value chains as value may be added locally and redistributed between stakeholders.

Lastly, the digital revolution is a megatrend that severely impacts technology development in every industry. Choosing technologies that can benefit from digital tools can highly increase the disruptive potential of technologies. This includes devices product development and optimization algorithms for technology design as well as advanced control algorithms for operation.

4.3 Examples for Potentially Disruptive Technologies in BES

Potentially disruptive technologies have been exemplarily chosen by assessing emerging technologies according to the developed strategies for disruptive technologies in BES. The qualitative assessment shown in Table 2 is based on a review of the corresponding technological literature and discussions among the authors and their colleagues.

Table 2: Examples for potentially disruptive technologies addressing strategies to promote disruption in BES

Strategies **Technologies**	Operational flexibility	Design flexibility	Material savings / abundancy	Electrification	Economies of scale	Integral design	Simplification	Energy efficiency	Trans-industrial applicability	Trans-regional applicability	Decentralization	Benefit from digital tools
Heat pumps	+		+	+				++	+	++		++
Li-Ion battery	++		−	++	++	+	+	+	++	++	++	++
Carnot battery	+		++	+	+	−	+	-		+	+	−
Liquid metal battery	++		++	+	+	−		+		+	+	−
Additive Manufacturing		++	++		−	++	+		++	++	++	++

4.3.1 Heat Pumps

Sector coupling technologies are key enablers to solve the issues of high shares of fluctuating RE in the grid. Moreover, sector coupling is a political goal. Sector coupling concepts for the German energy system are described in (Ausfelder *et al.*, 2017) and (Jansen and Sager-Klauß, 2017). A second main challenge is the decarbonization of the heating sector.

Heat pumps (HP) transfer heat from a source to a reservoir at higher temperature level by using e.g. an electricity-driven compressor. This conversion is far more efficient than the direct conversion of electricity to heat. Hence, they are a suitable option as heating (and cooling) device and offer the potential to strongly increase the share of RE in the heating sector. They are currently the only energy-efficient heating device that can make use of high RE shares in the electric grid. In combination with digital technologies they can offer flexible load control (Gellings, 1985, p. 1469).

The technical concept of HP is not new, but their market conditions are changing due to the increasing importance of the performance criterion “low CO_2 emissions”. There is a market pull for HPs, since new buildings often have low-temperature space heating systems (e.g. underfloor heating), which increases the efficiency of HPs. Adding to that, HPs fulfil the legal requirement of using environmental heat. Current market data show that the share of HPs in Germany has been increasing over the last years, reaching 40 % at newly built single and double family houses in 2017 and 18 % at newly build multi-family homes (Destatis, 2018). In renovation. At renovation of heating systems in existing buildings, HPs in Germany have a small, but also growing market share of 5.5 % (Bundesverband Wärmepumpe (BWP) e.V., 2018, p. 17). Grübler and Wilson (2014, pp. 118–130) emphasize the importance of supportive policies for HPs from analyzing historic R&D spendings and market data in several countries. To conclude, HPs are an example for potentially disruptive technologies where the disruption originates not from technical performance, but from changing markets.

4.3.2 Electrical Energy Storage Technologies

Large-scale energy storage options are a key enabler to solve the issues of high shares of fluctuating RE in the grid. However, they are still too expensive to compete with fossil fuels that can deliver energy on demand. Providing cheap, large-scale energy storage for electricity would contribute to economic performance, security of energy supply and low CO_2 emissions and lead to significant changes in the energy system. Key technical performance parameters include the overall efficiency, charging and discharging power, storage capacity and lifetime. All these parameters have to weighed against their contribution to the specific costs for storing electricity. Energy storage technologies are particularly sensitive to material scarcity, since their capacity depends on the mass of the storage material. Three promising examples, which make use of economies of scale due to large unit numbers or large size, are outlined below:

Li-Ion batteries can be used in many industrial applications. Currently, the chemistry of Li-Ion batteries is the most competitive in the mobile sector. Li-Ion batteries highly benefit from the economies of scale, which leads to rapidly decreasing costs and an increasing installed capacity. The economic learning rates of Li-Ion batteries are even higher than for PV (Kittner *et al.*, 2017).

A promising concept for district-scale electrical energy storage are high-temperature storages, also known as *Carnot batteries*. They convert excess RE into heat, which is stored in a storage material, e.g. in a packed bed, at high temperatures to limit exergy losses and which can in turn be reconverted into electricity by a heat powered cycle (Hänchen *et al.*, 2011; Steinmann *et al.*, 2019). Their main benefit are low costs, low cycle degradation (increased lifetime) and the use of earth-abundant materials. The concepts can be easily scaled to very large capacities without topological constraints and have a strong potential for sector-coupling. A key drawback is the low exergetic efficiency. However, the efficiency itself is not a direct stakeholder performance criterion, but rather specific costs.

Liquid metal batteries are another promising but still futuristic concept. The concept includes two liquid metal electrodes separated by a molten salt electrolyte and is described in (Kim *et al.*, 2013). Some of the technical advantages are high power densities, high energy densities and scalability. These attributes offer a high flexibility. Many of the possible electrode materials are earth-abundant and inexpensive and there are no topological constraints limiting them to certain regions. They promise very long lifecycles compared to conventional batteries because there are no electrode degradation mechanisms. However, further testing is necessary.

4.3.3 Additive Manufacturing

Additive Manufacturing (AM) describes the manufacturing of objects by adding up layers of material successively. As a first step, a topology is designed by using 3D modeling software The topology data is then input to a printing device that adds up layers resulting in a 3D object.

AM has some features that drastically increase the performance criteria of certain stakeholders. For engineers and manufacturers it allows new degrees of freedom in the design of components and therefore potentially increases technological performance (Thompson *et al.*, 2016). AM can increase energy-efficiency and material savings, which makes products more sustainable and can reduce costs for manufacturers and entrepreneurs if unit numbers are rather small. Moreover, compact and lightweight designs can reduce operation costs in the transportation sector. The applicability in several industries increases the disruptive potential of AM. With the possibility of integral design, technology performance can be optimized and thus surpass the minimum requirements of customers.

Since AM fosters rapid-prototyping, start-ups and entrepreneurs can significantly benefit from it by being able to produce and test prototypes of innovative products faster and cheaper. It therefore acts as a catalyst by altering the rate of improvement of other technologies.

A main restraint in the building sector is retrofitting the existing building stock. The high individuality of buildings and their heat supply systems makes automated and serial production solutions, e.g. for heating system refurbishment, difficult to implement. AM is well positioned to overcome this barrier. Since AM allows for customization and therefore higher customer value when customer-specific solutions are required, it may play a crucial role for retrofitting existing buildings.

AM has also the possibility to severely impact the value chain by enabling decentralized production. Manufacturing companies might outsource AM tasks to specialized AM manufacturers which can provide decentralized and flexible on-demand production services at the construction sites itself. This allows for new business models (Seyler, 2020; Petrick and Simpson, 2013). It is in particular promising in combination with digital technologies and algorithms, allowing for customized and optimized retrofitting solutions.

5 Summary and Conclusion

Based on an extensive literature review, innovation, disruption and disruptive technologies have been defined in the context of sociotechnical transitions. This includes a distinction between Disruption – a rapid transitional process, which has significant and long-term impact on stakeholders, technology stock and trends – and disruptive technologies, which significantly and rapidly increase customer value under current policy and market conditions and cause Disruption. Relevant current megatrends influencing BES have been mentioned and include amongst else the digital revolution, decarbonization, customization, urbanization, demographic change, resource scarcity and participation. The main stakeholders include building owners and users, energy suppliers, policy makers, entrepreneurs, engineers, craftsmen, and the public. The main performance criteria in BES are the meeting of comfort requirements within the building, economic performance, security of energy supply, low CO_2 emissions and safety. According to the above-mentioned criteria for disruptive technologies and the analysis of BES, strategies have been derived to promote disruptive technologies. Three emerging technology groups have a high alignment with those strategies and hence have been identified as potentially disruptive for BES, including

- flexible electricity-to-heat conversion devices, specifically heat pumps,
- electricity storage technologies, e.g. high-temperature thermal storages and batteries, and
- additive manufacturing of building parts or BES components.

Analyzing the market penetration of PV and HP systems in the context of current megatrends supports the conclusion that these two technologies are being disruptive for BES right now. Furthermore, it is likely that the identified technology groups will have a drastic impact on stakeholders and will reshape BES and the technological building stock until 2050. The high development potential of these technologies is further emphasized by the fact that they particularly benefit from combination with digital tools and algorithms.

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