HOW TECHNOLOGICAL FRAMES TRANSFORM:
THE CASE OF THE GLOBAL MICROGRID INDUSTRY

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INTRODUCTION

Global economic growth is based on a system that faces several sustainability challenges (Markard et al., 2012; Smith et al., 2010). Our industrial infrastructure, built on fossil fuels, is aging, antiquated, and requires substantial transformations (Rifkin, 2011). There is broad consensus that the economic narrative needs to be transformed to reflect these concerns and allow for sustainable energy generation. The role that technology plays for both economic growth (Acemoglu, 2012: 546) and the transition towards a more sustainable use of resources is substantial (Jacobsson & Bergek, 2011). Over the last decades, global warming resulting into an increasing frequency and severity of natural disasters (Hughes, 2015; Wang et al., 2016) has emphasised the importance of sustainable and resilient electrical power systems (Gilani et al., 2020).

Microgrids are a central building block in increasing the resilience, reliability, and sustainability of power networks. Microgrids, smaller localized grids, have been defined as "electricity distribution systems containing loads and distributed energy resources…that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded" (Marnay et al., 2015a). Distributed energy resources (DERs) are small, localized power generating units comprising technologies such as solar photovoltaic (PV), wind turbines, gas turbines, heat and electricity storage (Hatziargyriou et al., 2007; Lasseter et al., 2002). The disconnected or islanded operation allows microgrids to supply power during grid failures and provides them with the ability to improve the reliability and resilience of the main power grid. Advanced microgrids facilitate the integration of renewable energy resources to diversify the power mix and support the transformation to a more sustainable and cleaner energy generation (EERE, 2020; IEA, 2020b).

The 7 million km of transmission and 72 million km of distribution lines that make up the global electricity network (IEA, 2020b) are particularly vulnerable to extreme weather events. While power outages are not yet a significant problem in Europe, the last decade has shown how developed countries such as the United States can be repeatedly affected by outages due to an aging power infrastructure as well as increasing frequency and duration of extreme weather events. The United States reached 10 disaster events in the first six months of 2020 that caused material damage of at least USD 1 billion each. Between 1980 and 2020, the vast majority (90%) of years with 10 or more such devastating events were between 2008 and 2020, with only one year (1998) reaching that scale before in the aforementioned period (NOAA, 2020). An increase in microgrid adoption can relieve the pressure on electricity networks and reduce the need for long transmission and distribution lines which decreases energy losses and increases efficiency. Microgrids are also utilised as both an alternative and complementary option to the expansion of the centralized grid in order to electrify regions with limited access to a stable and reliable electricity network (Chaurey & Kandpal, 2010; Venkataramanan & Marnay, 2008). Overall, microgrids represent a technological innovation with ample relevance for management, organisation science, and policy researchers. It is argued that insights gained from studying microgrids can also be applied to other industries and product markets that face disruption through novel technologies.

Overarching approach and motivation for research

The main theme of this thesis is to explore the mechanisms through which an emergent, complex technology gains acceptance. To do so, I utilise three different perspectives that enable a focus on technology within the field of organisational science, an area of growing interest (Orlikowski & Scott, 2008).

Technology has been a central topic within the management literature with studies exploring the interaction between strategy and technology (e.g. Itami & Numagami, 1992), the effect of technology on performance (e.g. Powell & Dent-Micallef, 1997), technology diffusion (e.g. Geroski, 2000), technology in organisations (e.g. Orlikowski, 1992), or technology commercialisation (e.g. Markman et al., 2008).

I follow the long tradition of technology studies in management that trace and link industry dynamics to the evolution of technology (e.g. Bergek et al., 2008; Consoli, 2005; Grodal et al., 2015; Munir & Jones, 2004; Prencipe, 1997; Sinha & Noble, 2008) and studies that examine how technology influences institutions (e.g. Holmes Jr. et al., 2016; Lynn et al., 1996). This thesis is motivated by studies that have addressed criticisms by for example Orlikowski & Scott (2008: 466) to give technology a more central role within the management and organisation science literature. Studies of technological innovations such as those provided in Carlsson (1997) were an inspiration and the microgrid industry provided for a stimulating setting to apply technology-focused perspectives within management.

Microgrids using renewable energy resources are one promising solution to address existing weaknesses of electrical distribution networks (Gilani et al., 2020).

The microgrid market plays an integral part in the future energy system. However, considering its significance for the transformation towards a more sustainable energy sector, it has not received the attention it deserves outside the technical literature. This thesis brings management and organisational theories to bear on this problem, while developing new conceptual frameworks to help us understand how technologies are adopted and institutionalized. This thesis shows how technology-focused lenses within the cognitive frames and neo-institutional theory can be applied and hopefully encourages scholars to explore similar trajectories.

The thesis was further motivated by looking at solutions to the far-reaching consequences of the current energy transition and related problems. Microgrids have increasingly been proposed as a possible solution but are largely unknown to broader audiences. I therefore entered the field to explore how microgrids can contribute to the successful energy transition and what tensions exist that might hinder their adoption. It became clear that in order to pursue this route a deeper understanding of the technology and the markets through which it is bought, sold and eventually spread, is required. This motivated the industry study of paper one. The engagement with industry experts revealed that non-standardization of microgrid technologies is a key concern. This led to the second study to explore how the interpretation of a technology's capabilities, focusing on standardizability, changes over time and affects the technology's trajectory. This process unveiled that our understanding of how technologies become accepted often does not include the materiality of the technology as a central factor. This led to the third paper, that aims to give the technology itself a more central role in the proposed technology institutionalisation process model.

Structure of the thesis

The structure of this thesis is based on the three-paper model, which allowed me to study the broader phenomenon from three distinct technology-centred perspectives. This section provides a summary for each of the three papers that comprise my thesis.

Paper 1 is an in-depth industry study of the emergence of the power sector and the microgrid industry. It integrates the global microgrid market into the historical context of energy transitions and decentralization and elaborates the technology's relevance in these processes. Paper 1 raises theoretical questions on multiple levels that are explored along different trajectories in Paper 2 and 3.

Paper 2 applies the concept of complexity differentials to technological frames to provide new insights on frame transformation and destabilisation. This two-year qualitative study of the emerging microgrid market examines technological frames dynamics by considering the role of complexity.

Paper 3 is a conceptual contribution in form of a model of technology institutionalisation. The paper builds on insights gained while studying the microgrid industry and presents a conceptual model, to guide future studies of the technology institutionalisation process. The study utilises an institutional theory lens to shed light on the technology institutionalisation process applying a micro, technological/ organisational field, and macro level perspective.

In the following paragraphs, I briefly discuss each paper that comprises my thesis followed by a discussion about their interrelationships.

Paper 1

Paper 1, titled 'The global microgrid industry: Emergence and Evolution' is an industry study covering the electric power industry focusing on microgrids which play an integral role in the energy transformation towards a decentralized grid architecture. The industry study draws on a unique combination of archival data to provide a novel perspective on the microgrid technology and product market. Sources cover a wide spectrum from academic journal papers to practitioner industry proceedings, specialist industry publications, microgrid news websites and forums, consulting and research reports, as well as company white papers and websites. Paper 1 is organised into three parts: First, the historical dimension of the electric power industry is explored with an emphasis on energy transitions. Second, key aspects of modern energy systems such as distributed energy resources (DERs) and renewable energy sources (RESs) are introduced. The third and most elaborated part then covers the microgrid market and technologies. One central theme Paper 1 focuses on, is the decentralization process of the power grid architecture in which microgrids play an integral part.

The paper's main contribution is its unique perspective on the electric power industry and microgrid technologies reflecting recent developments by considering a wide spectrum of archival data sources. The industry study identified several theoretical issues that are further explored in Paper 2 and 3. One of the theoretical questions that arose was how frames specifically related to issues within the microgrid industry, such as the lack of standardization, change over time. A further question was related to the mechanisms that drive the institutionalisation of emerging technologies which is explored in Paper 3. Paper 1 acted as a foundational piece for the deeper theoretical explorations of this thesis. Paper 2, which is introduced next, uses the industry study of Paper 1. The empirical setting of the emerging microgrid industry is complex and dynamic. It thus required the deep understanding of the historical dimension, market drivers, stakeholders, benefits and barriers of the technology that was developed in Paper 1, to successfully engage with industry experts that were the main data source for the technological frames study of Paper 2.

Paper 2

Paper, 2 titled 'Technological Frames and Complexity Differentials: A Study of the Microgrid Industry and its Standardization Efforts', is a qualitative empirical study based on two years of data collection. The primary data source consists of in-depth semi-structured interviews with industry experts. This was complemented by data collected during field trips, practitioner conferences, numerous conversations with industry experts, and a comprehensive review of archival data. In paper 2, I draw on the concept of technological frames to develop the key contribution, which centers on the concept of complexity differentials. "Technological frames" (Orlikowski & Gash, 1994) guide interpretations among stakeholders regarding the value, function, and role of a technology (Gash & Orlikowski, 1991) and thus influence the dynamics of an evolving product market. Technological frames play a key role in guiding the evolution of product markets (Seidel et al., 2020) and provide for a useful lens to understand the effects complex technologies have on the perception of stakeholders (Davis & Hufnagel, 2007).

A main purpose of frames is to help decision-makers to make sense of an uncertain and complex environment and thus to define the dimensions that are important to assess the performance of a technology (McKenzie et al., 2009; Bateson, 1972). This study was motivated by my interest in better understanding the role of both technological frames and complexity in influencing the dynamics of an evolving product market. The focus hereby lies on complexity differentials between frames, technology, and the market. Whereas the majority of studies have examined the effect of frames on technology and innovation only few have focused on the content of the frames themselves (Grewatsch & Kleindienst, 2018). In their review, Cornelissen and Werner (2014: 203) called for further research that examines the "processual focus on how technological frames are constructed and evolve". The literature has not sufficiently examined the underlying mechanisms beyond political models that lead to dominant frames (Kaplan, 2008a) or the process by which frames are transformed and exchanged (El Sawy & Pauchant, 1988).

My exploratory research design allowed me to enter the field with the aim to better understand how technological frames develop and transform. The microgrid market, due to its relatively small size, offered the opportunity to conduct interviews with key actors to better understand market dynamics with the feasibility to reach theoretical saturation. In summary, our study contributes to technological frame research by introducing the concept of complexity differentials as a mechanism that influences frame stability. I describe how technological frames with high complexity differentials dampen market progress with a growing differential leading to increasing pressure for frame transformation.

This paper contributes to the debate on technological frames by highlighting the role of complexity and complexity differentials between the frame, technology, and the market. I argue that previous research has not sufficiently examined the role of 'complexity differentials' in determining the usefulness of technological frames. I refer to technological complexity as the perceived "existence of many interdependent variables in a given system, where more variables and higher interdependence mean greater complexity" (Rothwell, 2011: 562). Technological complexity differentials describe the difference between the complexity of a technology and the complexity of the technology's environment (Schneider et al., 2016: 4). I apply complexity differentials to technological frames as I find this concept provides a valuable perspective for technological frames studies in determining factors leading to frame transformation and destabilisation. Technological frames, technologies, and their respective product markets and industries vary in complexity. I find that technological frames that either oversimplify or overcomplicate the technology they describe, and as such extensively deviate in complexity, become instable over time ultimately leading to their transformation or overall replacement. This perspective adds to the literature that examines the limitations of frames such as encouraging overconfidence in a technology (Starbuck, 1989), inhibit learning and problem-solving processes (Bolman & Deal, 1991), or reinforcing "unreflective reliance on established assumptions" (Orlikowsi & Gash, 1994: 177).

I also extend the literature on technological frames from consumer goods to investment and industrial goods. Empirical technological frames studies have mainly focused on specific IT products. Examples are Orlikowski & Gash's (1994) study that examined the Notes system from Lotus Development Corporation. Mishra & Agarwal (2010) focused on the use of business-to-business (B2B) electronic markets for procurement.

The vast majority of technological frames studies are published in information systems journals (e.g. *ACM Transactions on Information Systems, European Journal of Information Systems, Information Systems Research, Information Technology for Development, Information Systems Journal, The Electronic Journal of Information Systems*) and technology focused journals such as '*Technology in Society'* or '*Information and Organization'.* This paper aims to encourage more organisational scholars to apply the technological frame's concept.

The next paragraph introduces the third paper which proceeds with the technology-focused approach by arguing the central role of technological fields within the technology institutionalisation process.

Paper 3

Paper 3, titled 'Technology institutionalisation: The Interplay of micro and macro mechanisms and field-level influences' is a conceptual study of technology institutionalisation. The findings of the study have led to a multi-level model of technology institutionalisation. The study is situated within the field of neo-institutional theory. In arguing for a more technology centred approach to investigate the institutionalisation process of novel technologies, the study conceptualises technology as an independent institution. The paper adds to technology-focused studies within institutional theory and addresses the call for multi-level models to explain the technology institutionalisation process. The technological field perspective allows for the consideration of technology-specific mechanisms that drive the institutionalisation process along with organisational field, micro, and macro mechanisms. A technological field refers to a 'social space' in which actors share a common meaning system related to a specific technology or set of technologies (Friedman, 1994b: 371; Granqvist, 2007: 9).

The paper argues that both organizational and technological field-level mechanisms influence technology institutionalisation by moderating isomorphic macro-level mechanisms and also directly influence the institutionalisation process. The multi-level model of technology institutionalisation proposed here emphasises that micro and macro-level of analysis should be regarded as complementary to each other and that both technological and organisational field-level mechanisms act as moderating forces within the technology institutionalisation process. The paper explores these interactions between micro and macro mechanisms while emphasising the importance of considering multiple moderating and direct field-level effects.

Interconnection between papers

The order of papers in this thesis reflects a progression from a practice oriented in-depth review of the microgrid industry and technology, to an empirical study that analyses the microgrid industry to investigate changes in technological frames, to a conceptual piece that uses insights gained during the research on microgrids to build a more abstract process model of technology institutionalisation that focuses on field-level mechanisms.

The papers use different lenses and concepts that allow for a deeper understanding of the technology and enable the incorporation of technology-specific mechanisms, in paper 2 these are conceptualised with the notion of a technological frames and in paper 3 with the notion of technological fields. The industry analysis of Paper 1 identified the lack of standardization in the microgrid industry as a major barrier. This lack of standardization is then explored in Paper 2 using a technological frames perspective. Paper 2 represents the central building block of this thesis. It builds on insights gained during the industry study in Paper 1. Paper 2 then spurred for the conceptualisation of the technology institutionalisation process described in Paper 3.

In the following chapters, I present the three papers that comprise my thesis.

PAPER ONE

THE GLOBAL MICROGRID INDUSTRY: EMERGENCE AND EVOLUTION

ABSTRACT

Distributed energy systems and microgrids in particular have received increasing attention over the last decade. Microgrids are recognised globally as an option to address concerns related to an aging grid infrastructure and the ongoing energy transition from fossil fuels towards renewable energy resources. However, despite the numerous benefits of microgrids there are also several barriers and disadvantages that have slowed down their diffusion rate. This paper discusses the development of the global microgrid industry in the context of historic and current energy transitions. Central to the current transition is the shift from a centralized to a more decentralized grid structure. It is argued that microgrids need to be understood considering the historic dimension of energy advancements and transitions. This study provides a timely comprehensive review of the global microgrid industry, its historical background, geographic comparison of market drivers, stakeholders, segments, benefits and shortcomings.

Keywords:

Distributed energy systems; Energy transitions; Microgrids; Renewable energy integration

1. INTRODUCTION

About 800 million people globally have no access to electricity (Ayaburi et al., 2020) and by the year 2040, global electricity demand is forecasted to be 60% higher than in 2017 (IEA, 2018). The electric power system is undergoing a vast reformation driven by a transition towards distributed energy resources (DERs) which often include carbon-free generating sources to address environmental concerns (Hanna et al., 2017). How can this decentralization process be supported while reducing energy poverty and meeting the growing global electricity demand? Microgrids represent an emerging and scalable technology to address this issue. Over the last decade the interest in the application of microgrids has been increasing around the world (Akinyele et al., 2018; Radhakrishnan et al., 2019). The growing attention can be related to the potential of microgrids to achieve higher supply reliability for energy consumers, supply energy to off-grid communities, increase grid resiliency, reduce emissions by integrating renewable energy resources, and possible economic benefits (AhmadiAhangar et al., 2019; Akinyele et al. 2018; Parhizi et al., 2015; Radhakrishnan et al., 2019). Microgrid technologies play a crucial role in the transition from fossil fuels to clean energy but the financeability of these systems remains often questioned by institutional investors (DOE, 2012; Strahl et al., 2015). Microgrids face numerous challenges in their diffusion process with the lack of standardization being a major factor (Guerrero & Tan, 2017).

The motivation for this study was to establish a comprehensive review of the microgrid industry and technology. Previous studies and reviews focused mainly on specific dimensions of the technology with few attempting to translate these findings into a review of current knowledge that covers the broader field. This industry study is based on a broad review of the literature related to the empirical phenomenon of the decentralisation transition of the electricity industry and the emergence of innovations in form of microgrids. I relied on numerous resources reaching from academic journal articles over conference proceedings and industry publications to press articles and online resources and platforms covering microgrid news and analyses. This work therefore represents a unique collection and systemic integration of resources about the power system in general and microgrids in particular. The study is inspired by traditional industry studies of which Carlsson (1997) as well as Mowery and Nelson (1999) provide a selection of good examples. The industry study attempts to identify the factors that have both driven and hindered the adoption of microgrid technologies and to illustrate cross-regional differences while integrating these current processes into the historical development of the electricity sector. I believe that this work is unique in relating the historical context to current advancements to explain how the microgrid technology emerged and grows. Another contribution is the consideration of a wide variety of sources (journal and magazine articles, microgrid online news platforms, industry and market research reports, and company websites) to shed light on the microgrid industry from several perspectives. Table 1 provides an overview of the data sources used for this review.

Table 1: Overview of Considered Data Sources

Type of Publication	Number of Publications cited
Journal Articles (e.g. *Energy Policy*)	110
Review Articles (e.g. *Renewable and Sustainable Energy Reviews)*	22
Conference Proceedings (e.g. *IEEE Electrical Power and Energy Conference)*	16
Books (Chapters)	12
Magazine Articles (e.g. *IEEE Power and Energy Magazine)*	17
Industry/ Market Research/ Consulting Reports (e.g. Navigant Research; GTM Research)	23
Company Websites	46

The structure of this review reflects three broad chapters. I will first cover the emergence of the electric network and major energy transitions to provide the background information that puts microgrids into their historical context (1). I then introduce the key components of the more decentralized energy system including distributed energy resources and renewable energy sources (2). I then cover the microgrid market and technology in depth (3).

2. THE EMERGENCE OF THE ELECTRIC NETWORK

The electric power system is an outstanding technical, economic, and scientific achievement that has drastically influenced society from its introduction in the 19th century (Hughes, 1993a). Electric power systems consist of power generation, transformation, utilization, and control components, as well as transmission and distribution networks (Hughes, 1993: 7). The power network utilises two primary systems, transmission and distribution with the former delivering power from generating stations to distribution substations and the latter delivering power from substations to end-consumers (Justo et al., 2013:390). Between 1880 and 1930 power generation consisted of prime movers such as steam engines as well as steam and water turbines with coupled generators. Transformers are responsible to change the characteristics of electricity supply during transmission and distribution. Energy utilization components included mainly lamps, motors, heating, and electro-chemical devices. Power transmission increased continuously during this period from short distances to thousands of miles. The control system regulates the supply system according to set voltage and frequency standards and optimises the performance of the system according to set goals such as efficiency and economic operation (Hughes, 1993a).

The electricity grid started with Edison's power plant of 1882 with small-scale distributed generation as a microgrid. This decentralized approach of electricity generation was the standard in the early stages of electric power distribution systems. As demand for electricity increased, electricity provision evolved towards power grids connected through long transmission lines and the transition from independent microgrid systems to centralized and regulated electricity grids to improve resilience and reduce costs (Jenkins et al., 2000; Su, 2017). Centralized electricity generation refers to large-scale thermal-based power stations that provide electricity to multiple end-users through transmission and distribution grids (EPA, 2018; McDonald, 2008). The development of building increasingly larger power stations reached its peak before the 1990s. Since then, the attempt to reduce both CO2 emissions and transportation losses while increasing energy efficiency and resilience, have contributed to a shift towards smaller, distributed energy systems (DES) (Hossain et al., 2019). DES are a solution to address these weaknesses and are an alternative to the conventional centralized fossil-fuel based energy system (Adil & Ko, 2016). Improvements in distributed energy resource (DER) technologies have further contributed towards this shift (Chakraborty, 2011).

2.1. Energy transitions

From the late 1880s until the early 1900s, the so called 'battle of the currents' (Hughes, 1958: 143) between direct current (DC) and alternating current (AC) took place (Sulzberger, 2003a; 2003b). The first public electricity supply in the world used AC power and was available in Godalming, UK from 1881. The Godalming system was, however, not sustainable and was abandoned in 1884 to revert to gas lighting (Strange, 1979). Holborn Viaduct power station in London, developed by Thomas Edison, opened in 1882 on a temporary basis. It was the world's first substantial generating station for public electricity supply and used DC power (Tucker, 1977). Later in 1882, Edison opened the permanent Pearl Street Station in New York City that used low-voltage DC. Edison proved that electricity generating stations using DC technology could be successfully deployed. Edison's dc systems were installed in numerous cities across the continent and dominated for several years (Sulzberger, 2003a). These small-scale generating systems were the original DC microgrids. However, the Edison electric system, based on low-voltage DC technology, had several limitations. The high cost for copper wire and high transmission losses limited the distance of customers to the generation station and thus the service area significantly. Consequently, the DC generating stations had to be small in size, thus limiting the exploitation of economies of scale in generation and leading to higher costs (Sulzberger, 2003a).

The invention of the transformer with the first commercial version developed by William Stanley available from 1886 with continuous improvements in the following years laid the foundation for the success of AC power enabling the adjustment of the voltage level (Guarnieri, 2013). A further milestone in AC technology development that resulted in severe competition to DC technology systems was Nikola Tesla's filing of seven patents in 1887. The patents made up the foundation for AC electric power generation and transmission that is still utilised today (Sulzberger, 2003a). The patents were purchased by George Westinghouse in 1888 who hired Tesla to develop and advance AC power systems. This marked the beginning the competition between Edison's DC and Westinghouse's AC system (Sulzberger, 2003b). Several key events ultimately led to the domination of AC systems and thus to a centralized grid architecture enabled through long distance transmission lines. These include the 1893 Chicago World's Fair, in which both Edison and Westinghouse competed to install their respective electric generation systems to light the venue. Westinghouse's AC system was able to offer the lighting for half the price as the DC system relied on a huge amount of expensive copper wire. The dominance of the AC system further strengthened by the decision to use an AC system for the Niagara Falls power station that went into operation in 1895 and further expanded until 1905. AC was critical to enable the long-distance power transmission from the Niagara Falls to Buffalo, New York (Sulzberger, 2003b). These events marked the beginning of a consolidation and centralization process driven by a rise in electricity demand (Hirsch et al., 2018). The success of the centralized grid architecture based on high voltage AC was driven by benefits of power transmission over long distances from large-scale power stations. This made it possible to exploit economies of scale in both transmission and generation, increased reliability from aggregating numerous generating units, and enabled numerous diverse loads on a single grid (Barker et al., 2001; Hirsch et al., 2018). Until the 1990s, the centralized grid based on large power stations located in mostly remote areas with long transmission lines to distribution points, was the established model. The development of these large, centralized power systems has been discouraged since the 1990s (Hossain et al., 2019) and we have seen a global trend back towards decentralization (Ajaz, 2019; Hirsch et al. 2018). The fundamental reason why AC power dominated DC power was the ability to adjust voltage levels of the former. As a consequence, during the 'battle of the currents', DC power had the disadvantage to be transmitted at the same low voltage as it was distributed to consumers. This required short distances of power plants to end-consumers to reduce transmission losses and resulted in small-scale power plants of which many were required (Purcell & Morin, 2013).

Centralized energy production, delivery and consumption contributed significantly to the economic growth in the 20th century. However, in the 21st century the nation-wide grid has started to show signs of decay and the advantages seem to have reached their limits. A report by the American Society of Civil Engineers found that aging equipment, limited capacity to manage increasing demand, and rising impacts of severe weather events, ultimately will lead to longer and more frequent power interruptions if the significant investment gap is not closed (ASCE, 2017, 2019). The European Union (Altmann et al., 2010), Asia (Taggart et al., 2011) as well as other regions worldwide face similar challenges but the motivations to shift from a centralized to a decentralized approach vary significantly depending on country and region (Ajaz, 2019; Hirsch et al., 2019). These and previously mentioned limitations of the centralized grid structure have led to an increasing effort in developing alternative approaches in form of decentralized energy systems (DES).

Historically, the electricity market represented regulated geographic monopolies with utility firms, driven by economies of scale and high fixed costs, in which generation, transmission, distribution, and retail supply were vertically integrated (Joskow, 2006:3). Electricity markets performed differently with developing countries not performing well as they faced high system losses and low labour productivity. Utilities in developed countries showed a better performance (Joskow, 1997; 2006) but also faced high operating and construction cost, wide performance gaps between firms, and high retail prices (Joskow, 1998; 2000; 2006). In order to address these limitations, the major reform goal has been to transform the electricity sector from a centralized to a more open and competitive structure (Reeves, 2013). The vertically integrated utilities were broken up into separate generation, retail, and network components. These deregulation and liberalization reforms had the aim to open-up electricity markets, optimise infrastructure use, and enable international trade. Retail reforms have enabled more consumers to choose their electricity supplier. There is significant uncertainty related to investments in power generation due to challenges related to the design and regulation of rapidly changing energy markets and slowing economic growth. Several drivers such as the move from fossil and nuclear to renewable electricity generation are causing a rapid change in energy markets requiring a new grid structure, market design, and regulations (Reeves, 2013). Decentralised energy systems play an important part in achieving reduced emissions and higher energy efficiency goals while ensuring a supply-demand balance. Microgrids are increasingly being integrated in energy networks to increase power supply security, reduce greenhouse gases, and as a method to manage peak loads (Marks et al., 2010; Wouters, 2015). The latter is referred to as peak load shaving and involves shifting loads from peak demand and supply to times of lower load to flatten the load curve (Nourai et al., 2008). Increasing peak loads, if not managed sufficiently, lead to power system instability which is a major concern of utility firms (Chua et al., 2016).

2.2. The electric power industry and reverse salients

The concept of a reverse salient refers to a component of a technological system that is falling behind other components due to its inefficiencies or uneconomical performance (Hughes, 1983; 1993b). The concept of a reverse salient applies to technological systems that are developed with a clear goal, such as to increase profitability, as only then the notion of 'falling behind components' is meaningful. Electrical systems provide good examples for goal-driven systems as operators have been concerned with minimising losses and costs while maximising profitability. As technological systems develop, reverse salients emerge, which are the parts of a system that require focused innovative efforts. Reverse salients provide a lens to link macro and micro-levels in a system analysis as they link the technological system to the wider society (Bijker et al., 2012).

A reverse salient emerges in a growing system when one system component is not well-aligned with or cannot develop at the same pace as the remaining system. This leads to reduced growth or stagnation of the system overall requiring corrective measures in form of concentrated invention and development actions to enable further expansion (Hughes, 1993). A reverse salient is the part of a technology system responsible for reduced growth due to uneven development of integrated components. Reverse salients or critical problems first need to be identified and defined to then focus inventive efforts to correct them (MacKenzie & Wajcman, 1999). They are often detected by system experts that analyse a growing system who find the reverse salient in form of inefficient and uneconomical components. The handling of reverse salients is in turn a major driver for inventive efforts and technological development (Hughes, 1993b). The efficiency of electrical power systems can be increased by for example changing the characteristics of a generator which in turn requires the change of characteristics of other components such as of the motor to eliminate it as a reverse salient (Bijker et al., 2012). A reverse salient differs from the concepts of disequilibrium or bottleneck in that it is more complex and includes the consideration of accidents and trends and thus suggests uneven change.

The electric power industry provides a good example for reverse salients as its development was significantly hindered due to high costs resulting from transmission and distribution losses. The reverse salient of uneconomical transmission of DC power systems could not be corrected in the 1880s resulting in the development of another system to provide a solution. Hughes (1993b) argued that the response to correct the reverse salients of the electric system was the invention and development of a new system. Edison's Pearl Street station that marked the beginning of the electric system in 1882 is usually regarded as a failure. Improvements of the DC system were largely ignored as the focus was mainly placed on the success of the rivalling AC system.

Improvements in DC generators, motors, and other components did not receive the attention they deserved. DC systems have had their advocates throughout history emphasising the profitability, reliability, and efficiency in densely populated environments. In the 1880s various improvements of the DC system ensured that reverse salients were eliminated which enabled the successful evolvement of the system for some time. The numerous patents that were filed during this time are evidence for the inventive effort and collective focus that was put into solving early critical problems. However, one reverse salient in form of high long-distance transmission and distribution costs could not be corrected. Edison identified the reverse salient while developing the DC system and responded two months after his Pear Street station opened by introducing, along other inventors, the three-wired distribution system. The three-wire system is still used today and saved 60% of copper wire needed compared to the usual two-wire DC system (Hughes, 1993b). The transmission and distribution reverse salient was also attempted to be solved by introducing battery storage technology in the DC power system. Cost-efficient high voltage DC was used for transmission and then fed into in series connected batteries to distribute the high voltage. After the batteries were charged, they were disconnected from generators and used to provide a low voltage to the distribution network. These battery technology advancements have often not received attention. The three simultaneous efforts, namely three-wired distribution system, battery technology integration, and high voltage DC systems, to reduce the high costs of low voltage DC transmission and distribution are proof of it being a reverse salient in the power industry. However, these inventions did not solve the reverse salient. Lucien Gaulard and John Gibbs achieved the breakthrough by showing that using transformers to regulate AC voltage results in an economic solution for long distance transmission of electricity. Transformers enabled high-voltage AC transmission and low voltage distribution solving the critical problem of high costs (Hughes, 1993b). Hughes (1993b) argued that this development can be described as an entire new system as opposed to advancing an old system due to several reasons. First, the AC system using transformers was already referred to as a new system during the time of the battle of the currents. Second, new components had to be introduced. Third, the analysis tools and engineering school courses differed between the AC and DC systems. It can therefore be concluded that there has been a process to move from one system (DC) to another (AC plus transformers) as the consequence from the former experiencing a reverse salient that was corrected by the latter. The majority of electricity networks have not been designed for intermittent power sources such as solar and wind. This intermittency makes back-up generation in form of fossil-fuel, hydroelectric and nuclear plants a requirement. However, with increasingly competitive pricing of solar and wind, such standby energy sources become less economical despite the continuing need for them. This makes subsidies in form of capacity payments inevitable. It therefore requires a transformation of the grid, so it has sufficient storage capacity, flexibility, and is smart in matching demand to supply (The Economist, 2017). Technologies related to energy efficiency have been found to diffuse slowly despite being profitable (Jaffe & Stavins, 1994). The explanation has been that potential developers do not possess the required competence, are not focused on investments in such technologies, and might not regard their return on investment as sufficient (Maribu et al., 2007). The current shift from an energy system based on converting fossil fuels to one relying on non-fossil and renewable energies is a challenge and will take a significant amount of time. The speed of advances of global renewable conversions was relatively slow in the past with wind, geothermal, solar, and modern biofuels contributing 0.45% in 1990 and 0.75% in 2008 of all primary energy. This expansion is significantly slower compared to growth rates of coal mining, oil extraction, or gas production during the first decades after these technologies were introduced (Smil, 2010b).

2.3. Drivers for the current transition

The current transition to a more decentralized or distributed grid architecture has several drivers that vary in strength depending on political, country-specific, and socioeconomic factors (Aguirre & Ibikunle, 2014; Marques et al. 2010). The major drivers for the current transition phase are the global rise in electricity demand, the policy efforts by governments to reduce carbon emissions, the need to make the traditional outdated grid infrastructure more reliable and capable to integrate renewable energy resources, and technological innovations that have reduced the costs for solar energy and storage systems (Daghrour & Al-Rhia, 2019; Hanna et al., 2017). Another driver is the fact that fossil fuels are depleting while the world population and energy demand is rising (Obara & Morel, 2017). In order to make the current energy transition a success, novel technologies need to be developed and integrated to make the power system more intelligent. The resulting energy network is also referred to as a smart-grids (Daghrour & Al-Rhia, 2019). The development of microgrids could facilitate smart grids (Mahmoud, 2017). Smart Grids are electrical networks that use a set of technologies to optimise the management and monitoring of generation, transmission, distribution, consumption, and business of the power grid (ibid., 2019). Their main benefit is to improve instantaneous grid power balancing and demand response (Mahmoud, 2017). The technologies within a smart grid vary and components are increasing but have always the purpose to maximise the operational efficiency of the overall system. Two further key factors driving the transition have been privatisation and deregulation efforts by many governments (Larsen & Bunn, 1999).

The transition away from the traditional centralized energy system based on fossil fuels is vital as the established system is not sustainable considering its adverse effects on society, economies, and the environment (Grubler, 2012). The current transition towards a cleaner energy system integrating renewable resources faces several challenges as it requires significant technological and regulatory changes as well as adaptations in tariffs, pricing models, and user behaviours (Sovacool, 2016; 2017). Further, history has shown that major energy transitions take several decades at least. It took coal more than 500 years from the first commercial coal mine to capturing 25 per cent of the global energy market. Oil required almost nine decades after the first commercial dwell was drilled to reach 25 per cent. Other sources have yet to reach that mark with nuclear energy currently covering five per cent and all renewables combined covering around 10 per cent of the global energy demand (IEA, 2018; Sovacool, 2017). It can therefore be expected that the ultimate replacement of fossil fuels by renewable energy will take several decades to complete. This lengthy innovation and diffusion phase of novel energy technologies can be partially explained by the complexity and size of the world's energy and infrastructural systems (Smil, 2012) and the energy's sector resistance to change due to long investment cycles of energy infrastructure and production projects (Lund, 2006; Sovacool, 2017).

In general, a good electrical network can be operated economically, possesses a high flexibility to respond to demand fluctuations, has the ability to connect all producers with consumers, and has a high reliability (Daghrour & Al-Rhia, 2019). The existing electricity grid is facing several challenges to fulfil these criteria. There is a rising global electricity demand with many regions still not being electrified. Demand also increasingly fluctuates between peak and non-peak hours which makes grid expansions necessary to reduce stress. In most markets there is an aging infrastructure that needs replacement to prevent a further increase in outages and blackouts as well as reducing transmission losses. The current grid also does not provide the flexibility required to efficiently integrate renewable energy sources to reduce carbon emissions and to match supply and demand in real time (Daghrour & Al-Rhia, 2019). The major issue with most renewable energy sources, such as wind and solar energy, are the variability of their outputs. This uncertainty can and often needs to be addressed by installing storage systems which represent a significant cost factor (Obara & Morel, 2017). The integration of renewable energy sources, distributed storage systems, and advanced communication technologies into the existing grid increases the complexity of the power system (Pourbabak & Kazemi, 2014). The resulting change in topology and creation of bidirectional power flows leads to difficulties in controlling such a system (Kar et al., 2014).

Despite the shift towards decentralization, the most likely scenario for the future energy system is a combination of centralized and decentralized sub-systems (Alanne & Saari, 2006). In developed countries, the transformation process from centralized to decentralized electricity generation is slowed down by already high electricity costs driven by aging networks, higher standards and fluctuations in electricity demand. The high prices may reduce the willingness to pay for additional expensive low-carbon investments (Reeves, 2013). The traditional profit oriented and regulated-monopoly business model was widely applied in the electricity industry and involves the ownership and operation of the generation, transmission, distribution, and related services by utilities (Bird & Hotaling, 2016; Joskow, 1997). The monopolistic structure of the electricity industry was justified by the infeasibility of competing transmission and distribution lines and by economies of scale due to large-scale generation (Borenstein & Bushnell, 2000). However, inefficiencies as well as reliability and resiliency issues of the centralised monopoly model did become obvious and were addressed with deregulation and restructuring (Bird & Hotaling, 2016). Deregulation has enabled third-party independent power suppliers to enter the industry which increased competition and provided consumers with choice (Joskow, 1997). This also acted as a driver for distributed generation (Zareipour et al., 2004), environmental concerns (Borenstein & Bushnell, 2015), and smart grids (Gungor et al., 2011). The latter referring to systems using bi-directional power and information flows to form distributed and automated energy delivery networks (Souran et al., 2016). Deregulation also led to an increase in small-scale power generation as large projects were perceived as too risky without the ability to transfer costs directly to customers (Zareipour et al., 2004). A further driver for the energy industry transformation has been renewable energy resources such as wind and solar PV which have become increasingly competitive to fossil-fuel-based generation due to technological advancements, economies of scale, improved supply chains, and increased developer expertise (Carrasco et al., 2006; IRENA, 2020; Rosa et al., 2018). Recent studies show that utility scale solar PV and onshore wind are now the most price competitive sources of newly build generation in almost all parts in the world and as a consequence contribute the most to newly added global capacity (BNEF, 2020; IRENA, 2020). Decreasing prices have made natural gas more attractive over recent years which has also significantly influenced the electricity industry (Bird & Hotaling, 2016: 4). In addition, there has been an increase in weather-related power outages in the US (Campbell, 2012) which resulted in substantial costs for society (Gholami et al., 2016). Rentschler et al. (2019) found that power outages due to natural shocks, in particular storms, were responsible for 55% of all recorded power supply disruptions in the US between 2000 and 2017. In Europe between 2010 and 2016 weather related outages accounted for 27% of total outages. Climate change is expected to further increase both frequency and intensity of natural shocks increasing the need for an improved power sector resilience (Nicolas et al., 2019). Microgrids have proven their value during such events providing power during severe disruptions (Bird & Hotaling, 16; Gholami et al., 2016). The combination of the various factors outlined above has provided microgrid technologies with the opportunity to become a valuable addition to the electricity network.

2.4. The current energy transition: a threat to incumbents

The growth in distributed generation in combination with increasing energy efficiency is a threat to the business model of utilities. Consumers in mature markets are increasingly becoming less dependent on the main grid due to the rise of distributed self-generation using mainly solar PV while the required electricity per household is declining due to efficiency gains. (Ganchinho et al., 2014; Sioshansi, 2016). Utilities will therefore have to adjust their business model in order to remain relevant. There are several disruptive factors for the existing utility industry. The ongoing advancements and declining costs of distributed energy resources are a major factor. There has also been an increase in consumer, regulatory, and political interests in demand-side management to reduce overall energy usage. A decline in economic growth has further impacted electricity consumption leading to a trend of rising electricity rates to compensate for falling demand. Government subsidies and other incentives to encourage selected technologies such as roof solar (Nersesian, 2016). Another factor has been the declining price of natural gas which has and will further replace other sources such as nuclear and oil to generate electricity (IEA, 2018). Earlier energy market reforms focused mainly on increasing competition for both generation and retail but did not reduce the utility's duty as a supplier of electricity to consumers. More recent developments driven by, amongst others, technological advances in distributed energy resources, demand management, and communication, have started the transformation process from one-way generation to a decentralized grid structure that will transform consumers to prosumers. This will require new business models and the creation of novel institutions offering a variety of new services to meet consumer demand. Competitively priced electric cars and the resulting higher adoption rate will further increase the need for this transformation (Reeves, 2013). There are several reasons for utility companies to be sceptical to the growing number of microgrids. Not all utilities have adopted the same stance towards microgrids. Some have been described as obstructers whereas other utilities have been actively involved in the development of microgrids (Wood, 2018b). Microgrids represent a threat to utilities and the overall electricity industry. They provide households and communities with the opportunity to supply their own power. Microgrid customers have a significantly reduced exposure to the increasing number of grid blackouts which affect millions of utility customers every year. Utility grids have become more affected by power outages. The increase in extreme weather events such as hurricane Sandy that led to over 8.5 million people losing access to power in 2012 and peak surges in electricity demand caused by extreme temperatures contribute to destabilising centralized power grids globally (Nersesian, 2016).

3. DISTRIBUTED ENERGY SYSTEMS, DISTRIBUTED GENERATION, DISTRIBUTED ENERGY RESOURCES, AND RENEWABLE ENERGY SOURCES

Distributed energy systems (DES) refer to energy systems with local energy conversion and thus short distances to energy consumers. A consequence of the DES concept is a reallocation of decision-making processes, know-how, ownership, and energy security responsibility (Alanne & Saari, 2006). DES significantly reduce the need for investments into the transmission network (Pepermans et al., 2005), are less vulnerable to external risks, and have the potential to decrease emissions due to reduced transmission losses and integration of novel technologies (Alanne & Saari, 2006). A DES can be compared to an information system, where decentralized systems are flexible, and risks are reduced through diversification. Information is, however, harder to find and the division of responsibility is less clear compared to a centralized system which is less flexible with more risks. In the past with higher limitations regarding information generation and processing, the traditional centralized energy system had advantages over a decentralized approach as it required significantly less effort in management and education (ibid., 2006).

The literature uses various definitions for **distributed generation (DG)**. A general definition proposed by Ackermann et al., (2001: 201) states: "Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter." 2017 marked the first year that the additions of annual installed power capacity of distributed generation exceeded centralized power plant capacity additions (Asmus, 2017; Gunjan, 2019).

Distributed energy resources (DER) are small-scale power-generating technologies that are located near to energy loads (Maribu et al., 2007). More specifically they are "electricity-producing resources or controllable loads that are directly connected to a local distribution system or connected to a host facility within the local distribution system" (IESO, 2019). DERs comprise several technologies, such as photovoltaic solar panels, diesel engines, combined heat and power (CHP) plants, electricity storage devices, small natural gas-fuelled generators, electric vehicles, small wind turbines etc. (ibid., 2019; Jiayi et al., 2008; NERC, 2017). DER installations are considered microgrids if they have clearly defined electrical boundaries, a master controller that controls and operates DERs and loads as a single entity, and if their generation capacity exceeds the peak critical load to enable a disconnection from the main grid and operate independently (Parhizi et al., 2015). Several studies (Gumerman et al., 2003; Iannucci et al., 2003) have examined the benefits of DERs which have significantly contributed to the decentralization process (Hirsch et al., 2018). The major benefits over centralized generation that were identified are reduced electricity costs, stable consumer electricity prices, increased reliability and quality, efficiency improvements, more consumer control, reduced security risk, reduced transmission losses, environmental emissions benefits, demand reduction, standby generation, and capacity deferral. However, there are also disadvantages related to the close proximity of DER units to people such as noise irritation and potential health risks due to indoor emissions (Gumernan et al., 2003).

Power generation from **renewable energy sources (RES)** has seen a significant growth since the 1990s worldwide (IEA, 2018). Despite this growth, coal is still the main source of electricity, contributing about 40% of global generation (IEA, 2018). The adoption of RES shows an asymmetry between developed and developing countries. There are, however, also significant differences in deployment levels between countries with similar economic and geographic backgrounds. The variations in the diffusion of RES can be attributed to political (feed-in tariffs, R&D investments), socioeconomic (income and energy consumption) and country-specific (RES potential depending of geography) factors (Aguirre & Ibikunle, 2014; Marques et al. 2010). The drivers behind the growth in renewable energy sources include policy support and government commitments in form of feed-in-tariffs and power purchase agreements as well as cost reductions of renewable technologies (IEA, 2018). Advancing technology and declining costs for renewables, wind and solar in particular, have increased demand and made them the fastest growing sources for global power generation (Usher, 2019). The rising market share of renewables is further supported by changes in the transport sector replacing cars using combustion with cars using electric engines. The increasing development and R&D related to electric vehicles contributes to advancements in battery technologies and economies of scale. This plays a vital role in the energy transition process due to the intermittent nature of wind and solar energy making energy storage a key factor (Usher, 2019). Wind turbines and photovoltaic systems can already generate competitively priced electricity further increasing consumer demand (Usher, 2019).

An illustration of the relatively slow progress in advancing modern renewable energy sources, is provided by **wind energy**. One of the first large-scale onshore wind farms opened in 1986 in Altamont Pass, California and had an average turbine capacity of 94 kW with the largest wind turbines generating 330 kW. Two decades later the average capacity of wind turbines reached 1 MW, nearly a ten-fold increase equivalent to a doubling every 5.5 years and the largest turbines reached 6 MW, a doubling of capacity every 4.4 years (Smil, 2010b). As of 2017, the largest wind turbine capacity is 9.5 MW and is for offshore use (MHI Vestas Offshore Wind, 2017), adding 3.5 MW to the turbines from over one decade ago, a 1.6 increase, not nearly a doubling of maximum capacity in the last decade. This illustrates how difficult it is to accelerate the pace of technical innovation related to renewable energies.

With regard to **solar photovoltaic (PV) energy**, there have been significant production cost reductions for PV cells from $100 per watt in 1970 to less than $1 per watt today (Smil, 2010b). One method to measure the competitiveness of the technology is grid parity, which is achieved when all electricity generated by the PV system can be sold at equal cost at which it may be purchased from the grid (Dufo-López & Bernal-Agustín, 2013 In: Sarasa-Maestro et al., 2019:1). In a recent study, Sarasa-Maestro et al. (2019) found that achieving grid parity for PV systems depends on their size with medium and large-scale installations already achieving grid-parity. Small systems will achieve grid parity depending on a sufficient financial model and overall costs. However, even with electricity production costs that are equal between PV systems and the existing electricity grid, the actual retail price of PV modules is much higher and further installation costs need to be also considered. In the U.S. the average system installed costs for residential systems was $2.70 per watt in 2018, $1.83 for commercial, and $1.13 for utility-scale PV systems. Major drivers behind these cost reductions are higher module efficiency, lower permitting and interconnection cost, lower inverter price, and particularly for residential systems higher labour productivity and reduced supply chain costs. The average PV system size, as measured by electricity produced, for commercial and residential systems has not changed significantly between 2010 and 2017 (Fu et al., 2018). PV cells vary drastically in efficiency levels depending on type. The efficiency of single-junction PV cells doubled from 8% to 16% between 1980 and 1995 and multiple-junction cells reached about 30% in 1995 (Smil, 2010b). In 2018, the common single-junction photovoltaic cells achieved an efficiency of around 22% (Multicrystalline silicon cells). Multiple-junction cells reached from 25% (Perovskite/Silicon) to 39% (5 Junction cell) (Green et al., 2018). These measurements are taken in labs and therefore do not consider efficiency reductions due to dust deposition and other limiting factors (Pan et al., 2019). This means that even under optimal conditions the performance of single-junction cells has only improved marginally, and multi-junction cells gained about 10% in the last two decades. The development for both wind and solar energy show that advances of renewable conversions have not been as rapid as sometimes portrayed (Smil, 2010b).

The capacity factor, the percentage of actual energy produced with respect to the maximum possible output in a given year (Nuno et al., 2018), also should be considered when examining the efficiency of renewable energy sources. Nuno and colleagues (2018) measured the real capacity factors of wind and solar energy in different regions and their results show capacity factors between 10% (Germany) and 20% (Spain) for solar energy and between 15% (Germany) and 24% (Spain) for wind energy. In comparison the capacity factor for coal powered plants was 54% (EIA, 2019b) and for nuclear energy 92.6% (EIA, 2019c) in 2018. As a consequence, in order to achieve high reliability using wind and solar generation requires a mix of energy storage, long-distance transmission, flexible generation, installation of more capacity, and demand management (Shaner et al., 2018). A broad adoption of DES and Microgrids would provide an alternative to these additionally required long-distance transmission lines.

The transformation of the electric grid is only feasible with the integration of energy storage as the technology is required to balance power fluctuations, shape peak demand, and enable the full use of intermittent renewable energy sources by making them dispatchable (Wold, 2019). **Energy storage systems** that meet grid interconnection standards (e.g. IEEE 1547 & UL 1741 for North America) lower costs by reducing custom engineering and site-specific approval processes (Kroposki et al., 2008a:2). Microgrids often require distributed storage technologies as in particular with the integration of renewable energy sources and resulting power fluctuations the generation and loads can often not be matched. Storage technologies allow the microgrid to meet power and energy requirements despite power fluctuations of primary energy sources. They also permit the distributed generation units to produce a "constant and stable output despite load fluctuations" (Kroposki et al., 2008a:2). Energy storage further supports power systems during peak electricity demand and provides a bridge during outages and disturbances (Kroposki et al., 2008b). Microgrids can utilise several forms of energy storage including different types of batteries, supercapacitors, and flywheels (ibid. 2008a). Batteries are direct current (DC) power systems that store electrical energy in form of chemical energy. Supercapacitors store energy electrostatically with no chemical reactions involved (Rufford et al., 2008). Flywheels store electrical power in form of rotational mechanical energy that can then be converted by generators into electrical power (Pena-Alzola et al., 2011). Energy storage systems are important in balancing power generation and energy demand (Eto et al., 2009) and improve the reliability of a microgrid (Hong et al., 2018). A storage system becomes essential when there is a cluster of microgrids in order to ensure an energy balance (Lasseter, 2002; Lasseter & Paigi, 2004). Micro-sources have large differences in response times. Storage devices therefore need to be integrated to deliver the required power to stabilise the system after events such as load changes and disturbances (Mahmoud, 2017). Some core requirements of microgrid energy storage systems are to:

a) mitigate fluctuations and ensure a balance between power generation and power consumption (Daud et al., 2013);
b) meet all energy demands when required and store energy during off-peak hours (Mahmoud, 2017:9);
c) enable a smooth transition from grid-connected to islanded operation and vice versa (Dali et al., 2010);
d) provide voltage support (Quesada et al., 2014) and to
e) regulate system frequency (Serban & Marinescu, 2014).

4. MICROGRIDS

Since the late 1990s solutions to manage the integration of DERs have been explored. Microgrids represent such a decentralized solution and are a central building block in the development of a new grid architecture (Hirsch et al., 2018). Although microgrids have been researched for over a decade (Soshinskaya et al., 2014), there is still no universally accepted definition of microgrids with ongoing discussions among experts to find a consensus (Farhangi, 2016; Olivares et al., 2014). However, a broadly cited definition states that microgrids are a “group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid connected and island mode" (DOE, 2012). Following this definition, a microgrid is "an integrated energy system consisting of DERs and multiple electrical loads operating as a single, autonomous grid either in parallel to or 'islanded' from the existing utility power grid" (Asmus et al., 2009:1). There are several basic technologies that need to be combined to make a microgrid. These are "distributed generation, distributed storage, interconnection switches, and control systems" (Kroposki et al., 2008a:1). Bob Lasseter, who coined the microgrid term in 2001, refers to microgrids as "self-contained electric systems that can seamlessly connect and disconnect from the main power grid" (Lasseter, In: Hubbuch, 2019). An alternative definition defines microgrids as "electricity distribution systems containing loads and distributed energy resources, such as distributed generators, storage devices, or controllable loads, that can be operated in a controlled, coordinated way either while connected to the main power network or while is landed" (CIGRÉ C6.22 Working Group). A microgrid can therefore function irrespective of whether connected or disconnected to the grid. There is no set capacity of the distributed energy resources (DERs) or description of the types and combinations of technologies that should be integrated into a microgrid (Hirsch et al., 2018:403).

An often referred to defining feature of a microgrid is its ability to disconnect from the main utility grid (Parhizi et al., 2015) which is also referred to as 'islanding'. The procedure to smoothly disconnect and reconnect to the main grid is highly complex and grid-connected microgrids may only island during power outages which is below one per cent of overall operating time (Cherian & Asmus, 2016). This has led to alternative definitions of microgrids not based on their islanding capability but to consider it as an option that may or may not be included. According to this perspective the key requirement of a microgrid is its ability to "actively manage power and energy flow within some defined ranges" (ibid., 2) and not solely its ability to island. Microgrid experts do, however, have contrasting views on this matter which has contributed to the difficulties in finding a universally accepted definition of microgrids (Cherian & Asmus, 2016). Islanding can be either intentional or unintentional. The former refers to the intentional disconnection of a microgrid from the main grid to initiate backup generation in cases of a maintenance or other planned activities. The latter refers to the disconnection of the microgrid due to disturbances in the grid (Llaria et al., 2011). Anti-islanding refers to a safety function that automatically shuts down grid-connected microgrids when an outage or fault in the main grid occurs to prevent unintentional islanding (McDonald, 2014).

Microgrids started with basic applications relying mainly on diesel generators and combined heat and power (CHP) systems. Early microgrids were isolated units with local control that were mainly adopted to increase power reliability. Over the last decade, microgrids have increasingly become more sophisticated and complex. Microgrids increasingly integrate renewable energy sources, energy storage systems, and advanced control and energy management technology. Microgrid evolution is further driven by increasing distributed energy resources capabilities and automation. Interoperability of microgrids is expected to increase with microgrid clusters becoming more common (GTM Research, 2014; Tweed, 2014).

Navigant Research (Asmus, 2018) has examined the yearly additions of distributed energy resources to microgrid capacity from 2010 to 2017. Energy storage has become a central component with strong growth from 2012 onwards. It can be noted that added wind energy capacity was stable with minor variations over the period examined. Capacity growth of solar PV was increasing steadily with stronger growth from 2015 onwards. Reciprocating engines including different kind of heat engines did make up a significant part of DER capacity additions. As of 2017, combined heat and power (CHP), which uses a heat engine to generate electricity and heat simultaneously, was the largest component (31%) in the DER technology mix used in microgrids. This was followed by Solar PV (19%), Diesel engines (18%), energy storage (11%), wind (7%), fuel cells (6%), Hydro energy (5%), and biomass accounting for 3% (Asmus, 2018). When compared to the forecasted scenario for 2027, solar PV is expected to increase by 10% to 29% of overall microgrid capacity. Energy storage is forecasted to more than double to 25%. Capacity share of all other components of the DER mix are expected to decline. Most notably CHP is forecasted to make up less than half (15%) in 2027 of its share in 2017. Diesel engines, despite a small decline, are forecasted to still make up a considerable 14% of DER technologies used in microgrids (Asmus, 2018).

Most distributed energy resources, such as wind turbines or solar PV, that are part of a microgrid system cannot be directly connected to the main distribution network due to the characteristics of the energy generated (Mahmoud, 2017). Power electronics interfaces are essential in microgrids as they convert the energy generated by the various DERs into grid compatible alternating current (AC) power. Solar photovoltaic (PV) systems produce direct current and require a DC/AC converter to be connected to the broader distribution network. Wind turbines already generate AC power, but frequency and phase might not be compatible with the grid, requiring an AC/AC converter to connect the distributed generation unit to the main grid (Kroposki et al., 2008).

Advanced control systems are indispensable for the stability and efficient operation of microgrids. The control system has the purpose to safely operate the system in both grid-connected and islanded mode (Kroposki et al. 2008a). The purpose of a control system is to regulate frequency and voltage, to ensure accurate load sharing and DER coordination, to control power flows and the synchronisation between the micro- and utility grid, and to optimise operating cost (Bidram & Davoudi, 2012; Mahmoud, 2017). The structure of a microgrid control system is hierarchical with "primary, secondary, and tertiary levels" (Bidram & Davoudi, 2012:1963). The primary level stabilises voltage and frequency, enables plug and play capabilities of DERs, optimises the share of active and reactive power among the distributed generators, and mitigates circulating currents. The secondary level of control, the microgrid central controller (MGCC), compensates for voltage and frequency deviations caused by the primary control. The tertiary control is responsible for the optimisation of both, the power flow between the microgrid and main grid and the economical operation (ibid.). There have been significant innovations in software controls for microgrids. This has contributed to strengthening the ability of microgrids to provide grid services. It has increased their acceptance as being a valuable part of providing grid stability as opposed to being mainly regarded as a threat to utilities (Wood, 2018b).

4.1. The history of microgrids

The first modern industrial microgrid in the USA was constructed in 1955 in Indiana (Asmus et al., 2009). However, the concept of a microgrid is much older as the power plant that Edison constructed in 1882 met already the criteria of a microgrid. There was no centralised grid established at that time, so his plant was self-contained, small with a limited distribution network, and with localised generation. It also already included batteries to provide energy storage (Wolf, 2017). Edison's firm continued to install another 57 microgrids in Manhattan until 1886. Thereafter, the electricity industry developed into a highly regulated monopoly market which led to a discontinuance of microgrid developments (Asmus, 2010). However, in more recent years, microgrids have experienced a revival. An event that has increased the awareness of microgrids was hurricane Sandy that hit the north-eastern part of the USA in 2012 and led to a significant loss of power in that region. However, some buildings were already equipped with either microgrids or distributed generation which allowed them to remain connected to power. This caught the attention of politicians and led to an increased integration of microgrids in the reconstruction of the power grid (Wolf, 2017). Scientists and engineers in the USA and Europe started in the late 1990s to explore solutions to integrate DERs into the grid architecture while maximizing reliability and resilience (Hirsch et al., 2018). This process led to the first foundational microgrid research programs that started with the Consortium for Electric Reliability Technology Solutions (CERTS) in the USA (Lasseter et al., 2002) and the European Union MICROGRIDS project (Hatziargyriou et al., 2006) in Europe (ibid., 2018). The CERTS project, founded in 1999, has been credited as the inventor of the modern microgrid concept (Lasseter et al., 2002; Lopes et al., 2013). Bob and Richard Lasseter (2001; 2002) introduced the concept of microgrids in the academic literature as a solution for the reliable integration of DERs and significantly contributed in pioneering the technology (Olivares et al., 2014). Microgrids face legal, regulatory, and technical challenges resulting in a still limited number of advanced commercial microgrids in operation (Akinyele et al. 2018; Hirsch et al. 2018; Yoldaş et al. 2017). The current energy regulations have not been sufficiently adjusted to allow for microgrid islanding, hindering progress with regard to this technology. A majority of the investments used to modernise the world's electric grid have instead been used for utility smart grid developments. Utilities focused on benefits that smart meter data delivers for them and did not focus on the consumer who often faced higher electricity bills as a result (Asmus, 2010). There has been an increasing awareness that the century old architecture of today's electricity grid needs to be updated. Its top-down structure based on unidirectional energy flows is not suitable to deal with today's challenges (Ackermann et al., 2001; Wouters, 2015). In case of a power outage this simple structure requires that all distributed generation, both renewable and fossil-fuelled, has to shut down. Here microgrids provide a valuable power source when the larger grid fails. Microgrids can shift the control of energy services from a centrally controlled to a local level and have thus represented a threat to some utility companies. Utilities have therefore contributed to hindering the growth of microgrids (Asmus et al., 2009). Microgrids can also be grouped according to the power system their operation is based on, namely alternating current (AC) and direct current (DC) Microgrids (Justo et al., 2013). AC microgrid systems utilise the existing standards for frequency, voltage, and operation for AC power networks (Justo et al., 2013). DC microgrid systems, on the contrary, maintain a DC bus to feed connected DC loads (Arif & Hasan, 2018). Advances in power electronics developments have enabled the voltage adjustment of DC power and thus have led to an increase of DC loads (Justo et al., 2013). The expanding use of DC devices such as solar PV systems have led to an increased consideration of DC microgrids (El-Shahat & Sumaiya, 2019). There are numerous DC devices requiring AC to DC conversion and DC based DG units that require the conversion from DC to AC to be compatible to the grid and often the repeated conversion to DC power required by many consumers. These conversions are often inefficient resulting in significant energy losses (Justo et al., 2013). DC microgrids can offer substantial efficiency, reliability, and stability gains (Peyghami et al., 2017).

4.2. Benefits of microgrids

The benefits of microgrids for different stakeholder groups have been widely documented in the literature (Savage et al., 2010; Parhizi et al., 2015; Venkataramanan & Marnay, 2008). Several technical, economic, and environmental benefits of microgrids have been identified (Chowdhury et al., 2009; Lopes et al., 2003; 2013). The decentralized architecture and consequential decrease of the distance between electricity generation and loads reduces transmission and distribution losses (Costa & Matos, 2009a) and feeder overload. Investments into transmission expansions and large-scale generating units can be reduced (Lopes et al., 2013). The voltage profile can be improved through a better reactive support of the power system (Madureira & Lopes, 2009). It has also been found that both power quality and reliability is improved. This effect can be attributed to an improved match of electricity demand and supply, a reduced impact of power outages, and improved voltage profiles (Madureira & Lopes, 2009; Lopes et al., 2013). Microgrids help to increase the number of participants in the electricity industry and thus reduce the market power of established firms. This may contribute to a reduction in the price of energy if network investments and distributed generation utilization is balanced (ibid., 2013). Microgrids can also provide ancillary services such as “reactive power/voltage control, active loss balancing, and demand (load) interruptions capability” (Gomes & Saraiva, 2010:1267). With regard to the environment, microgrids offer several advantages over large-scale centralized thermal power plants. Modern microgrids integrate renewable energy sources (RES) such as solar PV and wind turbines leading to a reduction of greenhouse gas emissions. Also, reducing the distance between power generation and consumption may increase the awareness of consumers to use energy rationally. Microgrids enable the integration of DERs while overcoming issues related to managing the various components within a network (Lasseter, 2002). The reliability of microgrids is superior to a traditional power system as a potential power failure has less impact and is better manageable due to the small-scale power generation (Bottrell, 2013; Hossain et al., 2019). There are also reduced transmission losses and improved network efficiency due to distributed generation (DG) units located closer to power consumers resulting in lower resistance in the transmission line (Chiradeja, 2005). In times of increasing power demand, microgrids reduce the stress on transmission and distribution infrastructure (McDermott & Dugan, 2002). Microgrids facilitate the integration of renewable energy sources as DG technologies are already often based on renewable energy (Hossain et al., 2019). Microgrids with their DG units can improve the control of power networks for power system operators due to the reduced distance, compared to centralized power stations, between power generation and load centres (Justo et al., 2013). As independent systems, microgrids are also a cost-effective solution to address low electrification rates of remote and underdeveloped areas (Su, 2017). Table 2 summarises the key benefits of the microgrid technology.

Table 2: Summary of Microgrid Benefits

Benefit	Reference
Enhance flexibility and resiliency of power networks	Dobakhshari et al. (2011)
Increase grid reliability and stability	Costa & Matos (2009b)
Integrate distributed energy resources (DERs)	Wang et al., (2015)
Enable islanded operation	Lasseter (2011)
Facilitate intermittent renewable energy integration	Venkataramanan & Marnay (2008)
Increase grid resilience	Colson et al. (2011)
Reduce impact of cyber attacks	Mo et al. (2011)
Reduce required investments in transmission and distribution networks	Basu et al., (2011)
Empower customers and end-users	Joos et al., (2017)
Provide ancillary services to the grid	Hatziargyriou et al., (2006)

4.3. Drivers for microgrid adoption

The shift from a centralized to decentralized grid architecture has numerous motivations but with regard to microgrids three broad drivers for DES can be identified: Resilience, emission reductions, and energy democracy (Ajaz, 2019).

4.3.1. Resiliency

In the context of energy systems, Bahramirad et al., (2015: 51) define resiliency as the "capability of power systems to withstand low-probability, high-impact events by minimizing possible power outages and quickly returning to normal operating state". Li et al., (2017: 1290) define resiliency as the ability "to prepare adequately for, respond comprehensively to, and recover rapidly from major disruptions due to extreme events". Resilience differs from reliability in that it corresponds to rare events with high impacts whereas reliability measures average system performance by the frequency and length of power outages from more common events (Li et al., 2017). Resilient energy systems are needed to cope with the increasing number of extreme weather events (Du & Li, 2019) as well as sabotage, terrorism (Laldjebaev et al., 2018), and cyber-attacks (Arghandeh et al., 2016). Decentralized energy systems, in particular as part of a network or cluster, are less vulnerable to such rare events (Alanna & Saari, 2006) and microgrids have been shown to increase the resilience of an energy system in several studies (Ajaz, 2019). In their review, Prehoda and colleagues (2017) find that United States military bases that adopted microgrids using solar PV generation have improved their resilience and the authors recommend an increased adoption of microgrid systems. Marney et al. (2015) show how two microgrids in Japan were fully operational during and after the earthquake and tsunami of 2011 to maintain critical infrastructure. The success contributed to actions by the Japanese government in 2014 to further strengthen the development of decentralized energy systems (ibid.).

4.3.2. Environment and transmission losses

Environmental concerns related to the impact of fossil-fuel based energy systems have been growing over the last three decades. Carbon emissions and related risks have gained awareness with a growing world population, rising industrial activity, and resulting increase in energy consumption (Dincer, 1999). In order to protect the environment and enable a sustainable development, the transition to energy resources that release no carbon emissions are key (Dincer & Rosen, 1998). There has been a substantial increase in the frequency and intensity of extreme weather and climate events over the last decade that are causing power outages (Climate Central, 2014). Urbanisation, the increased reliance on services requiring electricity, and longer durations of power outages contribute to a rising cost for societies, emphasising the growing need for grid resilience (Advisian, 2019; Mukherjee et al., 2018). Recent large-scale power outages in the US that affected millions of people show the vulnerability of the power grid (NOAA, 2019). It is therefore necessary to consider options such as microgrids to increase the resilience of the grid to minimise weather-related power outages (Mukhopadhyay & Hastak, 2016). Governments world-wide have recognised the significance of this transition which is shown by consistent global investments in renewable energy above USD 300 billion annually since 2015 with solar PV, wind, and hydropower being the largest contributors (IEA, 2019). A significant portion of renewable energy is in form of small-scale decentralized systems. Microgrids as integrators of distributed energy resources and renewable technologies into electricity distribution networks offer a promising approach for a sustainable energy sector (Bouzid et al., 2015; Lasseter et al., 2002). Therefore, the integration of a higher share of renewable technologies to reduce carbon emissions is a key driver for DES and microgrids (Chiradeja & Ramakumar 2004; Pasimeni, 2019). DES and microgrids also contribute to an increasing efficiency of the power system by cutting transmission losses by reducing the generation to consumption distance of electricity (Ackermann et al. 2001:199; Pepermans et al. 2005:789). The increase in energy efficiency through reduced transmission losses does not only reduce costs significantly but also reduces carbon emissions (Alanna & Saari, 2006; Sadegheih, 2010).

4.3.3. Energy democracy

Energy democracy refers to the active participation of people in energy transitions with the aim to increase democratic ownership and control of energy production and governance (Healy & Barry, 2017; Szulecki, 2018). Central to the concept of energy democracy is the transition from centralized to decentralized energy systems with a focus on integrating renewable energy resources (ibid., 2018). The decentralization and decarbonization of energy systems with increasing use of renewable energy is an opportunity to democratise the system.

The distributed energy resources can be adopted in various regions and enable a broad range of investors as opposed to large-scale centralized power plants (Szulecki, 2015; 2018). Microgrids as decentralized energy systems provide a solution to achieve energy democracy. The role of consumers of electricity is changing from pure consumers to also contributors of electricity during the decentralization process of the energy market (Pasimeni, 2019). Microgrids facilitate this transition towards prosumers (Watson, 2014) as they often directly involve end-customers in their adoption and diffusion (Sauter & Watson, 2007).

4.4. Microgrid disadvantages

Despite the numerous advantages microgrids offer, they also face several challenges. The knowledge and familiarity with regards to the operation, management, and control of microgrid systems is limited leading to potential technical issues (Chowdhury et al., 2009; Lopes et al., 2003; 2013). However, the ongoing research will help to overcome these difficulties (Asano et al., 2007). The design, availability, and acceptance of competitively priced technologies for installing and operating microgrids is one of the major challenges (Kroposki et al. 2008a). Barriers for the adoption of grid-tied microgrids are a lack of standardisation and regulations of key operations such as those related to connecting and disconnecting to the main grid (Ackermann et al., 2001; van Hende & Wouters, 2014).

Ajaz (2019) identifies high costs and the fact that microgrids are not necessarily environmentally friendly as the major disadvantages for microgrids. Microgrids as a "group of interconnected loads and distributed energy resources" (DOE, 2012) do not by definition integrate renewable energy sources. The combined share of CHP using fossil fuels and traditional diesel generation was 49% in 2017 with solar, wind, and hydro energy only contributing 31% (Asmus, 2018). This shows that an increase in microgrids that predominantly use fossil fuels as part of their DER mix do not contribute to reducing emissions (Ajaz, 2019; Hirsch et al., 2018).

Microgrids, despite their long history, are still seen as a new entrant in the energy market from a regulatory perspective. There is still a lack of regulations that determine under what rules microgrids can be operated, who can own microgrids, and what their legal standing is (Ajaz, 2019). In their review, Ali et al. (2017) found that regulatory and policy barriers are hindering microgrid diffusion. Formulation of specific regulations and policies for distributed generation and microgrids varies significantly with the EU being behind countries like the USA or China (ibid., 2017). Hirsch et al., (2018) identified two main legal questions affecting microgrids. First, should they be considered as electrical distribution utilities and thus regulated by state agencies? Second, can microgrids be successfully integrated into existing legal frameworks governing electricity trade, generation, and distribution? In order to increase the bankability of microgrids these legal questions need to be clearly answered to reduce uncertainty for investors (ibid. 2018; CEMTPP, 2010).

The relatively high costs to install microgrids are a barrier for adoption. It should, however, be noted that other energy and power infrastructure also tends to be expensive. Microgrid projects have a relatively high failure rate which is often due to extensive upfront analysis, feasibility studies, and design-building phases that are required when microgrids are labelled as infrastructure projects. The resulting high costs lead to misinterpretations of the value microgrids can deliver and discourage potential investors, developers, utilities, and consumers (Cherian & Asmus, 2016). Microgrid costs vary significantly depending on the segment and complexity of the project (Hernandez et al., 2018). In general, the costs for generation units represent the largest percentage in most segments regarding total system costs per megawatt. Energy storage systems contribute significantly to overall costs per megawatt with up to 25% for commercial microgrid projects. The high investment cost for sufficiently large energy storage systems (Safipour & Sadegh, 2018) is often regarded as a barrier for adoption but can reduce the operating cost of the microgrid (Abdulgalil et al., 2018; Xiong & Singh, 2015). Costs for microgrid controls vary significantly depending on the complexity of the system and make up 0.5% to 21% of total costs per MW (ibid., 2018). The costs for solar PV generation and battery storage have been falling rapidly and are on track or have already achieved to match traditional electricity sources making microgrids more price competitive (Bilakanti et al., 2018; Hirsch et al., 2018).

4.5. Microgrids as a threat

Microgrids have been described as a threat to utilities, but they can likewise support them in the challenging task of integrating distributed energy resources. Utility distribution microgrids (UDMs) serve the distribution as well as being a new platform for innovative services for customers (Asmus, 2016). Microgrids as a disruptor to the power sector can be compared with the introduction of the automobile which individualised passenger traffic unlike the earlier dependency on trains. However, for microgrids becoming widely adopted and as such to generate the bulk of electricity, they still have to meet many challenges. They need to become more affordable, demonstrate their reliability, efficiency, and invulnerability, as well as overcoming regulatory hurdles (Nersesian, 2016). Many utilities have been sceptical towards microgrids and regarded them as disruptors to their business model. There is a threat of reduced revenues for utilities due to microgrid customers generating and consuming their own energy. This is also referred to as the 'utility death spiral' where an increasing gap between the electricity tariff and costs for self-generation increases the adoption of distributed generation capacity such as solar PV (Castaneda et al., (2017). This ultimately leads to declining demand for utility generated electricity, which increases the costs for remaining utility customers and as a consequence leads to a further increase in self-generation (Hirsch et al., 2018). The result would be a state in which utilities cannot recover their costs. Also, the mostly grid-connected microgrids integrate renewable DERs which are difficult to manage for utilities for which they are seeking compensation from microgrid owners (Hirsch et al., 2018). Utilities make long-term investments into the grid infrastructure and increasing energy production by consumers make it more difficult to predict the output of energy that can be sold in the future to recover costs (Nersesian, 2016). One strategy to change the image of microgrids from being a threat to a valuable contribution to the grid is through energy market restructuring (Romankiewicz et al., 2014). Restructuring entails the unbundling of generation, transmission, and distribution services with independent power producers allowed to compete in the market (Hirsch et al., 2018). Services such as load-frequency control and local voltage support (Gomes & Saraiva, 2010) that microgrids can provide to the grid will be enhanced through real time electricity prices. This would allow microgrids to optimise the management of DERs and revenue streams. Market restructuring has, however, been slow and not universally applied (Borenstein & Bushnell, 2015). An important step in restructuring and to remove utility microgrid resistance is to decouple electric company revenues from electricity sales (Hirsch et al., 2018). This disassociation of a utility's revenues from its sales insulates the utility from sales fluctuations and ultimately transforms the utility from a commodity to an energy service provider (Eto et al., 1997). New business models for utilities have to reflect the new functions (e.g. resilience, power security, and renewable energy integration) that the utility grid is expected to provide which are fundamentally different to what utilities were responsible for in the past. A solution is to shift the approach from cost-of-service to performance-based, incentivising utilities to invest in grid infrastructure as opposed to maximising energy sales (Hirsch et al., 2018). Another factor that reduces the threat of microgrids is the possibility for utilities to get involved into the microgrid business themselves. Their existing customer base, knowledge, grid infrastructure, and franchise rights put utilities in a good position to provide microgrid services. This, however, is not universally allowed by regulators (Hirsch et al., 2018). One reason is that in restructured energy markets, where independent companies compete with utilities to supply power, utilities owning power generation infrastructure would have a competitive advantage. Here the defining question is whether microgrids should be considered power plants from a regulatory perspective. Another discussion is whether utilities may use ratepayers' money to pay for microgrid projects. Advocates argue microgrids contribute to overall grid stability and service quality and thus benefit the majority whereas opponents argue that microgrids only benefit a minority (Wood, 2017). The task for utilities in the future could be to connect the various grids to improve overall efficiency and reliability with the main electricity generation being supplied by microgrids. If microgrids succeed in becoming more bankable while convincing the market of their advantages, then they represent a valuable business model for utilities which need to find alternatives to outdated large-scale power plants. If utilities cannot adapt to the changing market structure, they eventually may face demise. Within the various drivers pushing the electricity market to a more decentralized structure, the declining costs for both solar power and battery storage technologies have been significant factors making distributed consumer owned electricity generation more competitive to rising utility rates. Customers defecting from the grid further increase the problems that utilities face (Nersesian, 2016).

4.6. Microgrid standardization

Microgrids face several issues related to a lack of standardization and regulations (Lopes et al., 2013). Microgrid projects are often highly customized, requiring expensive one-off engineering solutions and often depend on government subsidies as a consequence (Asmus et al., 2018). Standards are essential for microgrids to become an established part of the future energy system. Without standards microgrids could become prematurely obsolete or may cause security and safety issues. Also, a lack of standards may hinder future innovations and prevent the creation of a guiding framework for the development of renewable energy and related technologies (Daghrour & Al-Rhia, 2019). Further, only with standards sufficient economies of scale and scope can be established to create a competitive microgrid market and thus increase diffusion rates and benefits to the customer (Berker & Throndsen, 2017; NSTC, 2011). The following paragraphs provide an overview of existing microgrid standards.

4.6.1. Interconnection regulations

The various components of a microgrid are connected to the rest of the distribution system via an interconnection switch or point of common coupling. The microgrid faces the distribution network as a single controllable entity (Kroposki et al., 2008). Microgrids require standards that enable their interconnection with the utility grid as otherwise they are not able to operate in grid-connected mode to provide

lucrative grid services (Hirsch et al., 2018). Regulations for the connection of distributed generation to the main grid are therefore central for the business model of microgrids. Interconnection standards treat DER as potential sources of network faults. The underlying reason is the traditional centralized unidirectional operating paradigm of distribution networks which is fundamentally different to bidirectional power flows in decentralized systems. The anti-islanding requirements are an example of this attitude. This provision eliminates the possibility of DER to support a part of the power grid during an outage (Marnay et al., 2008) due to safety concerns (Asmus, 2014).
The understanding and evaluation of microgrid systems has shifted over the last decade. The view of microgrids as islanded systems with the main purpose of providing backup generation and load has become more nuanced to reflect their potential to become a valuable component of future power networks. In response to the growing influence of microgrids, the IEC established a system evaluation group (SEG 6) to identify the standardization progress and gaps, stakeholders, use cases, technology needs as well as to assess the overall microgrid market (La Fauci et al., 2018).

IEEE 1547 is a series of interconnection standards that receives regular development, updating, and revisions. The presence of multiple moving interconnection standards as part of the 1547 series but also related standards such as California's Rule 21 complicate and prolong integration and testing procedures (Bilakanti et al., 2018). The first of the series, the IEEE 1547 standard, approved as an American National Standard in 2003, laid the foundation for the safe interconnection of distributed energy resources with the distribution grid (Basso, 2014). Safety concerns were central to this standard with strict anti-islanding requirements to protect line workers and other grid participants. Until 2011 the main purpose of the 1547 series of standards and related interconnection policy was to ensure that DER would disconnect in the case of unintentional islanding (grid failure) as a safety measure to protect line workers. Then in 2011, IEEE 1547.4 was approved which is of key importance for microgrids as it regulates the design, operation, and integration of microgrids interconnected with the distribution grid and their safe intentional islanding and reconnection (Basso, 2014; Hirsch et al., 2018). However, even with the latest interconnection standards, there are several unresolved integration issues (Bilakanti et al., 2018). The latest revision in the series is IEEE standard 1547-2018 which mandates both voltage (VRT) and frequency ride-through (FRT) (ibid.). VRT and FRT standards require large-scale renewable energy resources such as wind-power plants to remain in service during a network fault (Zamani et al., 2014). The standard continues, however, to mandate strict anti-islanding requirements forcing the DER to disconnect from the main grid after detection of grid faults which interferes with VRT and FRT requirements. The Underwriter laboratories (Ul) 1741 safety standard also requires anti-islanding. However, many power inverter devices that are UI 1741 certified enable islanding, contradicting the anti-islanding requirement (Asmus, 2014). With growing deployment of DER this may affect power system stability and it shows there is still work required in revising and updating interconnection standards (Bilakanti et al., 2018). Microgrids challenge this anti-islanding requirement (Asmus, 2014). California's Rule 21 is a related series of standards that covers the operation of microgrids in both islanded and grid-connected mode, the transition between the two modes of operation, and the reconnection to the grid (Hirsch et al., 2018). Table 3 provides an extended list of the standards discussed above.

Table 3: Standards or Policies on Interconnection

Country	Standard
US	1. IEEE1547 2. IEEE1547.1 3. IEEE1547.2 4. IEEE1547.3 5. IEEE1547.4 6. FERC Order No.2006
California, US	1. Rule 21 2. California Interconnection Guidebook 3. Glossary and Resources Rule 21- Working Group 4. CEC 100-2005-003
Canada	1. CAN/CSA-C22.2 NO.257-06 2. CAN/CSA-C22.3 NO. 9-08
IEC	1. IEC/TS 62257.9.1 2. IEC/TS 62257.9.2
EU	EN 50438
UK	1. ER G59/1 2. ER G83/1 3. K/EL/00318/REP 4. ETR 113

Source: Qo, M., Marney, C., Zhou, N., (2011). *Microgrid Policy Review of Selected Major Countries, Regions, and Organizations*, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, p.7.

4.7. Bankability of microgrids

Microgrids have primarily been standalone government-funded projects and financial support from institutional investors is required to scale up the microgrid market to a viable asset class (Strahl et al., 2015). However, there have been concerns with regard to the bankability of microgrid projects. Achieving a sufficient rate-of-return on capital to ensure financial viability is one important aspect but a microgrid project should also address any risks that could harm financial returns in order to be truly bankable. The evaluation of the return on investment for microgrid projects is highly complex and reduces their financial attractiveness. It requires detailed knowledge about generation and load characteristics, utility and financing structures, energy markets, ownership models, regulatory environment, and individual project risks. Institutional investors have shown little interest in remote microgrid projects. This can be explained by the high risks, low expected returns on investment, and unclear policies that are often associated with microgrid projects (Williams et al., 2015). Monroy and Hernandez (2005) found that electrification projects in rural areas, such as those of remote microgrids, are typically offering unattractive risk-return trade-offs making it difficult to secure private capital. Several studies (e.g. Schäfer et al., 2011; Schmidt et al., 2013) have emphasized the need for more work exploring the reasons of and solution to the absence of private investors in electrification activities (Williams et al., 2015). It is argued here that a better understanding of the technological frames that shape the view of microgrids and their standardization potential contributes to problem-solving activities related to the insufficient bankability of microgrid projects. The microgrid industry needs to attract institutional investors to follow the growth trajectory of the solar photovoltaic industry. One key driver for solar energy has been innovative financing in form of solar power purchase agreements (PPA) models that reduce investment risk for buyers while offering sufficient returns to attract investors. A major barrier for microgrid investments can be related to their complexity as there are no established methods to evaluate some of the key benefits of microgrids such as resiliency (Siemens, 2016; Strahl et al., 2015).

4.8. Microgrid business models

Microgrid business models define how microgrid projects are planned and implemented to achieve set goals (Asmus & Lawrence, 2016). These goals reach from reducing energy costs, over improving resilience and reliability, to the value derived by the convenience to generate your own electricity (Hanna et al., 2017).

There are four common business models for microgrids: Energy as a Service (EaaS), utility rate base (URB), Government Energy Service Contracts (GOV), and Owner Financing and Maintenance (OF) also referred to as single user business model. 81 per cent of installed microgrids globally are using an Energy as a Service (EaaS) business model. However, when capacity as opposed to total numbers is examined, then business model market shares are relatively evenly divided. EaaS and utility rate base (URB) feature the same leading market share (22%) for microgrids deployed globally (Asmus, 2019). Table 4 compares the various business models according to their percentage share of total microgrid capacity.

Table 4: Microgrid Business Models' Share of Capacity

Business Models	**% of Capacity (2Q2019)**
Energy as a Service (EaaS)	22
Utility rate base (URB)	22
Government Energy Service Contracts (GOV)	20
Owner Financing and Maintenance (OF) Single User	21
Other	15

Source: Asmus, P., (2019)

In the long-term **Energy as a Service (EaaS)** is expected to become the leading business model. Examples of EaaS offerings include the provision of energy to data centres or charging stations for electric cars (Weil, 2018). EaaS includes power purchase agreements (PPAs), pay-as-you-go and other programs. The latter is often applied to smaller remote microgrids. The EaaS business model will particularly increase within the commercial and industrial (C&I) microgrid segment as it addresses the segment's demand for microgrids as a service and converts capital expenses into operating costs (Aram, 2017). EaaS can drive microgrid growth in a similar way that the solar lease model drove solar PV system growth. It has, however, be noticed that microgrids are considerably more complex than PV systems and thus also entail more risk (Wood, 2018b). The complexity of microgrid projects stems from the broad range of factors that need to be considered such as the appropriate choice of technology, financing solutions, local policies and regulations, procurement policies, and utility needs (Aram, 2017).

Power Purchase Agreements (PPAs) have gained importance as the common business model applied to solar PV projects. PPAs are performance-based contracts between energy consumers and producers that aim to reduce the risk for the parties involved in the agreement (Mendicino et al., 2019). Customers face no upfront costs and energy services are often priced similar or below to what the local utility firm is charging. PPAs for microgrids have increased over recent years and are particularly suited for private sector owned grid-tied microgrid projects. Microgrids deployed using PPAs have higher risks compared to solar PV systems due to their complexity and resulting performance risks. To reduce performance risks, customization needs to be limited (Asmus & Lawrence, 2016).

Owner Financing and Maintenance or single owner business models refer to one entity that finances and maintains the microgrid (Asmus & Lawrence, 2016). It is the simplest among all available models and widely applied for grid-tied microgrids in particular in the campus microgrid segment. This business model is mostly applied to simple microgrids. The business model is likely changing to a EaaS model with increasing complexity of the microgrid due to the integration of additional components such as renewable energy sources and/or storage systems.

The utility rate base model (URB) refers to microgrids that are deployed by utility firms which place their development and maintenance costs into their rate base and recover costs by charging users (Asmus & Lawrence, 2016). The rate base refers to the book value of the utility's capital investment (Myers, 1972). This business model is mainly applied by public utilities that operate in remote areas with no grid connection (Asmus & Lawrence, 2016).

Government Energy Service Contracts (GOV) include two common approaches: Energy savings performance contracts (ESPC) are long-term contracts based on identified and quantified energy savings that can be achieved through the integration of microgrids. ESPCs are therefore often used to improve the energy efficiency of existing projects. Utility energy services contracts (UESC) involve a utility firm with the aim to realise economies of scale (Asmus & Lawrence, 2016).

4.9. The global microgrid market

The microgrid market has recently entered the growth phase but is still relatively immature (Asmus et al., 2018). As of the third quarter of 2020 there have been 7,968 microgrid projects identified representing 34.6 gigawatts (GW) of planned and installed power capacity (Guidehouse, 2020). The valuation of the global microgrid market varies significantly across the different research firms. According to Navigant Research, the global microgrids market had a value of $6.3 billion in 2018 (Francklyn, 2018) with Pioneer Reports valuing it at $11.4 billion (Pioneer Reports, 2019) and imarc (2019) stating a value of $19.3 billion for the same year. Global Data (2018) assigned a value of $15bn and Market Research Future a value of $18.7 billion for 2017 (Market Watch, 2019). The forecasted market value also differs among the research firms. Navigant expects the microgrid market to be worth $30.9 billion by 2027 (Francklyn, 2018). Global Data (2018) predicts a $30 billion market already by 2022. Market Research Future expects a value of $33 billion by 2023 (Market Watch, 2019) and imarc forecasts a value of $36.3 billion by 2024 (imarc, 2019). Microgrid market growth is driven by increased government support. An example is the government of India that plans to implement 10,000 microgrid systems. Other governments also have ambitious microgrid investment plans. This is reflected by microgrids' expected 23.5% share of total electricity access investments globally between 2018 and 2030 (Mortier, 2019).

Microgrids have a global presence, but the market size as measured by total installed capacity varies significantly. As of 2019, Asia Pacific and North America are the leading microgrid markets with 37 and 33 per cent market share respectively. The Middle East & Africa and Europe follow with 14 and 11 per cent. Latin America is the region with the lowest installed microgrid capacity only accounting for 5 per cent (Asmus, 2019). While costs for different types of microgrids vary widely (Giraldez et al., (2018), overall microgrid costs have been declining. The drivers behind these cost reductions are falling prices of major microgrid components such as solar PV, wind, and battery storage technologies. The variance in costs is however high as it is affected by the size of the microgrid system, the vendors, manufacturers, type, controls used, and application. The microgrid controls have the highest cost differences due to different required complexity levels (Wood, 2018b).

The microgrid market (Mishra et al., 2020) and its number of vendors have been increasing over the last years (Wood, 2018b). Major drivers of this growth have been battery manufacturing and microgrid control companies (ibid., 2018). There are, however, major corporations that previously entered the microgrid business and have then decided to discontinue their involvement. Examples of such companies are

Boeing, Bosch and Hitachi (Wood, 2018b). Despite the widely recognised benefits of microgrids, the microgrid market has long remained behind projected commercial growth (Soshinskaya et al., 2014). Among the most significant barriers for microgrid adoption in developed countries are standards and interconnection issues (Tweed, 2014). Modern microgrids that integrate renewable energy sources require advanced storage technologies to ensure uninterrupted power supply. Improvements in both batteries as well as inverters have contributed to the growth of the microgrid market (imarc, 2019). Increasing threats involving cyber-attacks on power systems require novel security measures. Microgrids can supply high-risk sectors with power without being dependent on external power and communication technologies. Another driver is the aim to reduce transmission losses over long distances for which microgrids with their local power generation are a solution (imarc, 2019). The spending on infrastructure projects has been increasing due to population growth and urbanization in emerging countries such as China, India, and Mexico. This increases power demand substantially and drives microgrid implementation (Gran View Research, 2017). Low prices for natural gas are a further driver for more advanced microgrids (Tweed, 2014). Despite not part of the formal definition of microgrids, renewable energy sources such as solar PV and wind have become an important component of modern microgrids (Hafez & Bhattacharya, 2012; Su et al., 2013). The growth of renewable power generation is therefore an opportunity for microgrid diffusion.

4.9.1. Actors driving microgrid adoption

Microgrids are complex projects that require several actors to collaborate to successfully plan, adopt, and operate (Soshinskaya et al., 2014; Warneryd et al., 2020). Microgrids differ from other decentralised energy systems such as solar PV systems for homes. Integrating microgrids into the existing grid infrastructure is challenging as they act as a parallel system that interferes with the macro power grid. They therefore may compete with utilities and have to meet stricter regulations (Ajaz & Bernell, 2020). High complexity and costs have led to a frontrunner role of state-related entities, such as university campuses or military bases, in early microgrid adoption (Aram, 2017; Hanna et al., 2017). Despite cross-country and regional differences, it can be concluded that government affiliated agencies play a central role in microgrid adoptions.

Government agencies provided the majority of investments in early microgrid developments in the USA. In recent years large companies, banks, and utility firms have started to contribute to microgrid adoptions by privately financing projects (Roosa, 2021:219). The development of microgrids to foster sustainable energy production is increasingly driven by public-private partnerships (PPPs). The cooperation among stakeholders resulting from such partnerships is often represented by community microgrids (Roosa, 2021:226).

Commercial and industrial (C&I) companies represent a major market segment for microgrids (Asmus, 2019). Such companies finance microgrid projects either to secure their energy needs in off-grid areas, locations with unreliable power, or due to economic and environmental reasons (WBCSD, 2017).

The complexity of microgrids requires a revision of existing regulations and legislations to remove adoption barriers for actors (Warneryd et al., 2020). State actors in areas that suffer more from natural disasters, such as the United States and China, are more likely to be concerned regarding grid resilience and drive microgrid adoption compared to areas where such landscape factors are less frequent (Ajaz, 2019; Navigant Research, 2017a). Within large countries such as the United States, regions that experience repeated natural disasters such as California, state actors are more often involved in microgrid adoption (ibid., 2019).

State and federal actors are important decision-makers driving microgrid deployment through influencing policy, funding, and market demand (Feng et al., 2018; Warneryd et al., 2020). In the EU the European Commission drives numerous microgrid development programmes (ibid., 2020). Utility firms responsible for the local electricity grid also play a central role in microgrid deployments (Feng et al., 2018). Another group of key actors are technology providers that provide essential technology integration, development, and testing services for microgrid operations (Warneryd et al., 2020). In recent years financial investors, such as the Carlyle Group, have started to enter the microgrid market. Financial services firms often utilise an energy-as-a-service business model to operate microgrids and are increasingly establishing themselves as key actors (Spector, 2018). An example of how various actors are required to work together to realise a microgrid project in the United States is provided by Carter and colleagues (2019). For the Blue Lake Rancheria (BLR) Microgrid project, the California Energy Commission was the primary funding provider. The project leader, primary contractor, and engineering manager was the

Schatz Energy Research Center (SERC) located at the Humboldt State University. PG&E, the responsible utility firm, permitted and supported the project. BLR is the site host and owner of the microgrid (Carter et al., 2019; Warneryd et al., 2020). The microgrid adoption decision is commonly made by governmental agencies or research programs due to their high costs and still existing lack of regulations regarding their long-term value creation (Martin-Martinez et al., 2016; Warneryd et al., 2020). Table 5 provides an overview of key actors involved in the adoption decision.

Table 5: Key Actors by Country

Country/ Political Union	Key Actor Examples	Description
Australia	Australian Renewable Energy Agency (ARENA)	Governmental agency to manage Australia's renewable energy programs
	Council of Australian Governments (COAG) Energy Council	Ministerial forum for the energy sectors
	Australian Energy Market Operator (AEMO)	Agency responsible for coordinating the electricity market
China	State Council of the People's Republic of China	Executive branch of the central government
	National Energy Administration	Policy coordination agency
Japan	New Energy and Industrial Technology Development Organization (NEDO)	National research and development agency
EU	European Commission (EC)	Executive branch of the European Union
	E.ON	Utility
South Korea	Ministry for Trade, Industry and Energy (MOTIE)	Agency regulating economic policy of the country's energy sectors
Taiwan	Ministry of Economic Affairs (MOEA)	Ministry responsible for formulating policy and laws for the energy sector
USA	New York State Energy Research and Development Authority (NYSERDA)	Public-benefit corporation
	California Energy Commission	State agency responsible for energy policy and planning
	ComEd (Illinois)	Utility
	PG&E (California)	Utility

Adapted from: Warneryd et al. (2020)

4.9.2. Major industry players

The microgrid industry continues to become more fragmented with more players entering due to improved opportunities. The spectrum of players reaches from highly specialised firms covering niche product offerings to fully vertically integrated companies that both manufacture and distribute whole microgrid systems globally. Van den Berg et al., (2016), in their strategic analysis, grouped microgrid firms into three broad categories. First, there are large incumbents consisting of leading industrial manufacturers such as ABB, Schneider Electric, S&C Electric, and Siemens. The vertically integrated companies develop, manufacture, and distribute the technologies that microgrid end-customers such as utility firms require. Second, smaller new entrants that develop business models for software-based products related to renewable energy, grid management, and other grid infrastructure. The third group are system integrators that use components developed by group 1 and 2 to package microgrids systems for customers. Further, the authors name six major microgrid market stakeholders: "component manufacturing, systems engineering, system integration, installation and configuration, testing and certification, and operations and maintenance" (Van den Berg et al., 2016:9). In the following paragraphs a selection of key microgrid developers is introduced and collaborations between leading firms are discussed. Table 6 shows key microgrid firms along with their leading microgrid product.

Table 6: Microgrid Industry: Selection of Key Players and Products

Company	Key Microgrid Products
Large industrial developers:	
ABB	Microgrid Plus System, PowerStore, MGHS100
Duke Energy	Microgrid Energy Solutions
Emerson Electric	Ovation microgrid control system
Engie	Giga Storage, HyESS, PowerCorner, PowerHouse control system, Prophet EMS microgrid optimization and control
General Electric	GridIQ microgrid control system, Mutilin U90 Plus Generation Optimizer
Hitachi ABB	e-mesh, PowerStore
S&C Electric	GridMaster Microgrid Control System
Schneider Electric	EcoStruxure Microgrid Advisior,
Siemens	SICAM control and monitoring system, Spectrum Power: Grid control solutions
Distributed generation developers:	
Bloom Energy	AlwaysON Microgrids, Bloom Energy Server
Enchanted Rock	Integrated Reliability on Call (iROC)
Gridscape	EnergyScope Microgrid Controller
PowerSecure	PowerBlock Generation Systems, NexGear Switchgear
Tecogen	InVerde e+ system
Tesla	Powerpack and Powerwall battery systems, Solar Roof

Asea Brown Boveri (ABB), established in 1988 through a merger between Allmänna Svenska Elektriska Aktiebolaget (ASEA) of Sweden and Brown, Boveri & Compagnie (BBC) of Switzerland, is headquartered in Zurich, Switzerland (ABB, 2020a). ABB is a provider of power and automation technologies. The company offers a broad range of products and services to improve power grid reliability, increase industrial productivity, and enhance energy efficiency (ABB, 2020b; Bloomberg, 2020a). ABB has been a frontrunner in the microgrid industry providing off-grid microgrids to remote locations for over 18 years (Wood, 2016b). The microgrid business was significantly strengthened in 2011 when ABB acquired Powercorp, an Australian renewable power automation company specialised in control solutions to manage the integration of renewable energy generation into microgrids. Powercorp's flywheel-based system to stabilize frequency and voltage of microgrids was also a valuable addition to ABB's microgrid business (ABB, 2011). In 2016 there were several strategic initiatives to further strengthen ABB's microgrid business. ABB formed a strategic partnership with the Indian Institute of Technology Madras to build advanced microgrids and improve rural electrification (ABB, 2016a). This partnership is a driver for the Indian microgrid market. Also, in 2016, ABB launched a modular and scalable "plug and play" microgrid solution (ABB, 2016b) providing it with a competitive edge in the global microgrid market. A partnership between ABB, the Australian Renewable Energy Agency (ARENA), SunPower, and SunSHIFT has led to the world's first portable hybrid microgrid (ABB, 2016c). The portable hybrid microgrid combines "solar modules, conventional diesel/gas generators and optional energy storage" (Simpson, 2016). ABB and Rolls-Royce announced in 2019 a worldwide partnership on microgrid technologies and innovative automation to offer microgrid solutions for utilities, commercial and industrial entities (ABB, 2019).

Duke Energy is an electric power holding company that owns and operates diverse power generation assets in the Americas (Duke Energy, 2020a; Bloomberg, 2020g). Duke Energy has been a provider of microgrid solutions since 2013. As part of its microgrid developments the company also collaborated with Schneider Electric and Siemens (Duke Energy, 2020b).

Engie SA is a French multinational electric utility firm that offers electricity, natural gas and energy services (Engie, 2020a). Through its EPS technological division and its Smart Cities activities, Engie offers decentralised energy generation, energy storage systems, and microgrid solutions (Engie, 2018; Engie, 2020b). A key product in its microgrid business is PowerCorner, which is a containerised microgrid solution designed for rural environments based on a combination of generators, PV systems and battery technology (Engie, 2016).

S&C Electric, founded in 1911, is a manufacturer and global provider of electric power systems, equipment, and services specialising in system switching, protection and control (Bloomberg, 2020f; S&C, 2020a). The company is an established microgrid provider offering a leading microgrid control system (GridMaster) and complete solutions (S&C, 2020b).

Siemens AG, established 1847 and headquartered in Munich, Germany, is a leading electronics and electrical engineering company. Siemens mainly operates in the fields of electrification and power, automation and control, transportation, and medical diagnosis (Bloomberg, 2020b; Siemens, 2020a). Siemens is a major player in the microgrid business with a comprehensive portfolio of products, solutions, and services (Siemens, 2020b). In late 2015 Siemens and LO3 formed a partnership to collaborate on microgrid projects with the Brooklyn Microgrid being the first project. The Brooklyn Microgrid integrates solar PV to generate local electricity. Excess energy is sold to neighbours via peer-to-peer transactions using blockchain technology. The technology enables to count up and log every unit of energy created within the microgrid. These units of energy are then sold and bought in the community. In 2017 Siemens invested in LO3 Energy to strengthen the existing partnership (LO3 Energy, 2016; Siemens, 2017). In 2018 Siemens and Solarkiosk joined forces with the aim to develop microgrid solutions for rural off-grid areas in Africa (Siemens, 2018).

General Electric (GE), founded in 1892, is an industrial conglomerate headquartered in Boston, United States. GE is a diversified industrial, infrastructure and financial services corporation operating within power, renewable energy, aviation, and healthcare industries (Bloomberg, 2020c; GE, 2020). GE acquired the power and grid businesses of Alstom in 2015 to combine its Digital Energy business with Alstom Grid to form Grid Solutions (GS), a joint venture of GE and Alstom (GE, 2015). GS provides products and services to enable utilities and industry to effectively manage electricity from generation to consumption. This includes microgrid solutions for remote, utility, campus, military, smart city, and industrial sites (ibid., 2015).

Hitachi, Ltd., headquartered in Tokyo, Japan is a diversified multinational manufacturer of equipment, machinery, and services for e.g. the power, communications, and consumer electronics sectors (Bloomberg, 2020d). In mid-2020

Hitachi and ABB created a joint venture called *Hitachi ABB Power Grids* with the aim to become a leading power systems firm that amongst several activities will develop microgrid solutions (HitachiABB, 2020).

Emerson Electric Co, founded 1890, is an American diversified manufacturing company operating in two broad business segments: 'Automation Solutions' which includes its electrical components products and distributed microgrid controller and control systems as well as 'Commercial & Residential Solutions' (Bloomberg, 2020e; Emerson, 2020).

Schneider Electric SE, founded in 1995 and headquartered in France, is a multinational provider of electrical power products (Bloomberg, 2020h). Amongst a broad portfolio of microgrid solutions, the firm has recently started to offer modular microgrids in combination with an energy-as-a-service (EaaS) business model (John, 2020). The following paragraph offers an overview of specialised microgrid providers.

PowerSecure Inc, founded in 2000, and a subsidiary of Southern Company, a utility holding company, is a leading provider of distributed generation systems including advanced microgrid solutions (Bloomberg, 2020i; PowerSecure, 2020). According to company data it is the largest microgrid developer in the United States with 2 GW of installed and 1.6GW of controlled distributed generation systems (Southern Company, 2019).

Bloom Energy was founded in 2001 and offers specialised distributed power generation equipment (Bloomberg, 2020j). The firm's 'Energy Server' platform, the central building block of its microgrid solutions, is a customisable power generator utilising solid oxide fuel cell technology (Bloom Energy, 2019; 2020).

Enchanted Rock ltd, founded in 2006, is an American provider of natural gas-fuelled microgrid solutions (Enchanted Rock, 2020). The firm specialises in providing resiliency microgrid technology to critical infrastructure sectors (Microgrid Knowledge, 2020).

Gridscape Solutions, founded in 2012, is a Californian company specialised in smart energy systems including microgrids and electric vehicle charging systems (Gridscape, 2018a). The firm through its EnergyScope product line offers resource management systems for distributed energy resources and microgrid controllers (Gridscape, 2018b).

Tecogen, a provider of Combined Heat and Power (CHP) distributed generation systems, was founded in 2000 and offers packaged CHP microgrids (Tecogen, 2020).

Tesla, founded in 2003, provides electric vehicles, battery technology, and distributed energy solutions including microgrids to a wide range of customers including commercial organisations and utility firms (Bloomberg, 2020k; Tesla, 2020a; b).

4.9.3. Geographic differences in microgrid adoption and drivers

Microgrids are adopted globally but there are major geographic differences in both market share and growth drivers. It can be observed that the scope and purpose of microgrid projects differ from country to country. Countries have different visions and requirements regarding the future of the power grid and face diverse challenges related to the required investments in their power grids. Some countries focus mainly on increasing the share of renewable energies whereas others want to improve the reliability and resilience of their grid (Daghrour & Al-Rhia, 2019). Whereas the US mainly requires investments into the aging grid infrastructure, Europe has reached a point where the further integration of renewables, particularly wind and solar, has become a challenge, and developing countries mainly in the Sub-Saharan region suffer from low electrification rates (John, 2013). In the US electricity prices have increased by over 12 per cent in the last decade (EIA, 2019a) with also substantial increases in the amount customers pay for grid infrastructure. However, the number of outages and their duration have increased at the same time. This can be interpreted as a sign for diminishing returns of grid investments (John, 2013). Microgrids are a promising alternative to substantial investments in the aging centralized grid infrastructure. Many countries also have restrictions on new transmission and distribution networks further strengthening the case for microgrids (Farzan et al., 2013). There are significant differences in the motivation to install microgrids between regions.

Microgrid market drivers can be broadly grouped into those applicable to developed regions with an existing grid infrastructure and those drivers applicable to regions where electrification rates are below average (Hirsch et al., 2018). Some drivers such as fuel and cost savings as well as improved ancillary grid services are important to all regions (Hirsch et al., 2018). The developing world faces substantially different challenges as there are still close to 800 million people with no access to electricity (Ayaburi et al., 2020) and continued rapid population growth in the least developed countries (United Nations, 2019). Countries with lowest electrification rates are predominantly located in sub-Saharan Africa and the region is expected to gain more than one billion people between 2019 and 2050 (ibid., 2019). Unreliable power has a negative effect on healthcare, education, and the environment (Practical Action, 2013; 2018). Renewable energy sources provide the least expensive option to provide electricity access to remote areas largely due to the declining costs of small-scale solar photovoltaic (PV) systems (IEA, 2018). Microgrid technologies can therefore have a particular high impact in these regions. North America has seen a high growth on decentralized power generation in the industrial and municipal sector to increase the independence from the main grid. This development has a positive impact on microgrid market growth. The manufacturing and construction sector growth in Asia Pacific in combination with regulatory support promotes infrastructure investments with microgrids expected to benefit in particular in markets such as China and India. In Central & South America the abundance of mineral reserves and resulting need for distributed power generation is regarded as a major driver for microgrid market growth (Grand View Research, 2017). Table 7 provides a summary of the key differences in microgrid adoption drivers across regions.

Table 7: Regional Differences in Microgrid Adoption Drivers

Region	Main Driver for Microgrid Adoption
North America	Aging Grid Infrastructure and Natural Disasters
Europe	Integration of Renewable Energy
Asia-Pacific	Meet growing demand and electrification of remote areas
Middle East and Africa	Electrification of rural areas
Central and South America	Reduce network losses
World	Fuel and cost savings, improving grid stability

4.9.4. Microgrid markets

The following paragraphs present information about the global distribution of and regional differences in microgrid diffusion and capacity.

a) North America

North America, despite being outperformed by the Asia-Pacific region in terms of overall microgrid capacity, the region is still leading in grid-tied microgrids. The second largest microgrid market is mainly driven by the United States (Wood, 2018b). Market growth can be attributed to a growing need to improve resilience and reliability of the electricity grid. The US, in particular the North-Eastern region, faces a combination of outdated electrical grid infrastructure and an increasing number of severe weather events leading to power outages and significant costs. Microgrids are possible solutions to replace aged generation units and support the existing transmission and distribution system (Hirsch et al., 2018). Microgrids have been installed to protect critical facilities such as hospitals (Stluka et al., 2011), water supply, transportation, and information systems against blackouts (Abbey et al., 2014) but are increasingly applied to whole communities (Mengelkamp et al., 2018).

b) United States

When only countries are considered, then the U.S. has the highest microgrid capacity share in the world (Ajaz, 2019). Regional climatical and geographical differences are important factors determining DER attractiveness. The U.S. covers a broad range of these factors leading to significant differences in DER adoption across the country. The West-Coast with its densely populated regions in California, above average electricity prices, and a cooling and heating demand, is an attractive market for DER expansion. The North-eastern U.S. also represents a market with good DER potential. This potential is less pronounced in the Midwest and smallest in the south due to low electricity rates (Maribu et al., 2007). In a recent quantitative study, Ajaz (2019) examined microgrid adoption in the U.S. and found that states with higher frequencies of extreme weather events are more like to adopt microgrids. The author, in line with previous studies (Che et al., 2014; Lu et al., 2015; Marnay et al., 2015b), found that a key driver behind the adoption are resilience concerns that are higher in states that experience such disasters more frequently. Ajaz (2019) found that a 1% increase in disaster frequency led to a 0.06% increase in number of microgrid projects. It can be concluded that resilience to disasters contributes to grid decentralization (Khan, 2018). The study also shows that public support for energy choice and the environment does not significantly increase microgrid adoption. (Ajaz, 2019). The increase in both frequency and severity of extreme weather and climate events that are causing power outages (Climate Central, 2014) shows the inability of the current electricity grid infrastructure to deal with this change, providing an opportunity for microgrids (Ajaz, 2019). The U.S. National Academy of Engineering named the electricity system as one of the 20 greatest engineering achievements of the 20th century (Constable et al., 2003). The current condition of the energy infrastructure in the U.S. does, however, not reflect this achievement with consistently bad ratings by the American Socierty of Civil Engineers (ASCE, 2019). The significant progress in the development of microgrids and their increasing technical and economic feasibility (Hirsch et al., 2018; Schneider et al., 2016) shows that microgrids, still being a niche innovation, can become a competitor to incumbent technologies further driven by the growing need for resilience (Ajaz, 2019).

c) Europe

Europe is only the fourth biggest microgrid market with 11 per cent of capacity (Asmus, 2019). This can be partially explained by the high existing grid reliability (Eurelectric, 2013; Fairley, 2014) which reduces the motivation to install microgrids based on power outages. Growth for Europe's microgrid market is expected to be limited with the reduced need for new remote systems being a factor (Wood, 2018b). Distribution system operators (DSOs) in Europe face an increasing difficulty in integrating decentralised renewable energy sources with high variability in generation as well as new loads such as electric cars. The rising share of renewable energy makes investments into the distribution infrastructure necessary to maintain the high levels of reliability which will also increase microgrid investments (Eurelectric, 2013).

In Europe, the reduction of global warming through the integration of renewable energy generation has been the major driver for microgrid adoption. Microgrids enable the local balancing of power supply and demand facilitating the integration of distributed energy resources. A major advantage of microgrids over standalone DERs, such as simple solar home systems using photovoltaic solar energy and battery storage, is their appearance as a single unit to the distribution utility. This significantly reduces the number of sources and consumers of electricity that have to be managed and coordinated and enables the modification of net load profiles to optimise the main grid (Lasseter et al., 2002). In Europe significant investments in transmission lines are required since utility scale renewable generation is often far away from the demand for electricity. The required grid expansion depends on the target for greenhouse gas

(GHG) emissions with ambitious reductions of 80% until 2050 requiring almost twice the investment and expansion length compared to 40% reductions (Egerer et al., 2013). Microgrids are flexible systems that facilitate the integration of DERs including renewable energy sources and can therefore be a solution for Europe's transmission problem. Europe has less and shorter power outages compared to the US (Campbell, 2012) but still faces a reliability challenge. Utilities and grid operators in Europe have to ensure that renewable energy sources such as wind and solar PV are integrated without endangering the stability of the grid network (Hirsch et al., 2018). The government funded fast increase of wind and solar power capacity has not been met with the required modernisation and expansion of grid infrastructure (Jorge & Hertwich, 2014). Major grid expansions and additional storage capacities are required as a consequence (Hammons, 2008; Müller et al., 2013). Major investments in new transmission lines are for example required to effectively accommodate the power produced by offshore wind parks (Bresesti et al., 2008). Jorge and Hertwich (2014) examined the effect on the environment resulting from the transition to a renewable power system. The authors, focusing on CO2 emissions from building the required additions of transmission infrastructure, found that projects for new and updated lines will emit significant amounts of CO2 which need to be considered when analysing the integration of renewable power sources. Microgrids minimise the distance between power generation and consumption and have therefore the potential to reduce CO2 emissions otherwise required for building new grid infrastructure to accommodate renewable energy. Microgrids also reduce the complexity of controlling a huge amount of DER which facilitates the integration of new DER capacity in Europe. Microgrids integrate several DER and appear to the utility firm as a single source (Lasseter et al. 2002).

Electricity prices in the European Union are the highest in the world and are forecasted to modestly increase (IEA, 2018). This development further incentivises firms and individuals alike to consider the investment in distributed electricity generation. Utility rates are increasing due to required works on dated transmission, distribution, and generation systems, new investments in smart grids, increasing operating costs, and reduced demand due to higher energy efficiency and increasing consumer owned electricity generation. The reduced demand leads to a lower utilization rate of existing centralized power plants which ultimately forces utilities to increase rates (Nersesian, 2016).

d) Asia Pacific

Asia Pacific (APAC) is the largest microgrid market with 37 per cent of overall capacity (Asmus, 2019). The region has surpassed North America as the largest microgrid market due to its significant population growth and less developed power grid infrastructure. The latter particularly drives the adoption of remote microgrids. Major markets within the APAC region are Australia, China, India, and Japan (Wood, 2018b). A significant number of microgrids deployed in the Asia Pacific region are small and in remote locations often with mobile phone towers as main loads (Asmus, 2014). The insufficient grid infrastructure and population growth creates opportunities for remote microgrids (Wood, 2018b). Companies have been increasingly investing in microgrid development in the APAP region. A significant number of microgrids are, however, demonstration projects with no clear business model attached. In order to advance the adoption and implementation of economical microgrids in the region, suitable business models need to be found. Overall, the forecast for the APAC microgrid market is positive with companies such as ABB and Schneider Electric predicting major growth in particular for remote, community, and industrial microgrids (Research and Markets, 2018). The APAC region comprises several developing nations and rural areas with insufficient energy infrastructure and resulting unreliable power quality and low electrification rates. The high number of islands in the region further complicate the building of required grid infrastructure. Microgrids are therefore an opportunity for the region to increase its electrification rate and reduce investments on transmission infrastructure (BIS Research 2018; Sriram, 2011).

e) Middle East & Africa

The Middle East & Africa is the third largest microgrid market with 14 per cent of total capacity (Asmus, 2019). Africa faces significant challenges due to energy poverty (Batinge et al., 2019) with a significant amount of the population (ca. 57%) in Sub-Saharan African countries lacking access to reliable electricity (Cozzi et al., 2018), there is potential for microgrids to address this need. Costs to expand the existing power grid to unelectrified regions are high and most often exceed the costs for microgrids. Many households in rural sub-Saharan countries rely on biomass to cover their energy needs leading to high emission rates. The integration of renewable energy sources into microgrids will contribute to cut greenhouse gas emissions. The region benefits from good conditions for both solar PV and wind as renewable energy sources (Longe et al., 2013). Countries with an insufficient grid infrastructure provide a good opportunity for microgrids as the relationship between a microgrid's effectiveness and tying into an existing grid benefits them (Hubble & Ustun, 2016). However, despite the good growth potential for microgrids in the Middle East & Africa region, the pace of microgrid development has been limited. The lack of private sector investments has slowed down added capacity. Reasons for insufficient microgrid investment are unfavourable policies and utility rates. Utility rates in most emerging economies are often too low to enable a sufficient return on investment for microgrid investors (Reber & Booth, 2018). The rates often do not reflect the cost of service due to government subsidised utilities and donor-funded infrastructure projects (Bardouille et al., 2012). Microgrids do not receive the same subsidy benefit but are in many regions expected to offer a rate comparable to utilities and thus do not have a cost advantage which hinders their diffusion (Schnitzer et al., 2014). Stable cost-reflective rates and cost-recovery mechanisms are required to attract private investors and scale-up microgrid projects (Reber & Booth, 2018). Investments in microgrid projects in the Middle East region have been limited and insufficient planning has further reduced adoption rates. Barriers for microgrid adoption are heavily subsidised utility electricity rates. However, there is increased effort to implement subsidy reform policies and mechanisms to accelerate the modernisation of the grid infrastructure. Local utilities, technology firms, and governments need to collaborate with international microgrid vendors to facilitate microgrid diffusion in the Middle East (SEI, 2019).

f) Central and South America

Central and South America is the least developed market for microgrids with only 5 per cent of capacity (Asmus, 2019). Electricity generation in most Central and South American countries relies heavily on fossil fuels. The region has integrated significant conventional renewable energy generation into its power mix consisting of mainly large hydro power plants (De Nigris & Coviello, 2012). Hydro energy contributes to 51 per cent of power generation in the region (IEA, 2018) and renewable energy sources (i.e. wind, solar, biomass) only make up 12 percent of power generation capacity (IEA, 2018). Power generation in Central and South America is mainly centralised with negligible distributed generation. Countries in this region plan to increase the share of decentralised renewable energy sources in the energy mix which will also benefit microgrids. The expected added distributed generation capacity for the region until 2023 is however behind all other regions (IEA, 2018). The limited growth potential for microgrids can be attributed to high electrification rates across the region with the exception of some remote areas which offer an opportunity for remote microgrids (Macri, 2017). Microgrids would be beneficial to reduce network losses and improve the energy management of mega-cities in the region (De Nigris & Coviello, 2012).

4.9.5. Global microgrid market by end-use

Microgrids can be broadly categorized into either grid-connected or remote systems. As of 2018, remote microgrids represented 41 per cent of total microgrid power capacity in the world. The remainder of 59 per cent represent the various microgrid segments that are grid-connected but do have the ability to be operated in island mode. The grid-tied market is therefore significantly larger than the remote segment representing 1,463 MW of annual capacity compared to 1,231 MW for remote systems in 2018. This gap of 232 MW is expected to further grow to 7,346 MW by 2027, with remote systems accounting for 4,230 MW and 11,576 MW for grid-tied systems (Wood, 2018). This development can be explained by the preference for grid-tied systems in developed markets such as North America (Asmus, 2019).

Asmus et al. (2009) identify six major microgrid applications. First, community microgrids, with communities referring to geographic regions including residential customers. It is expected that standardization needs to progress, and regulatory barriers removed in order to achieve broad commercial acceptance of this class. Second, commercial/industrial microgrids, such as those used in the petrochemical industry. Third, institutional/campus microgrids offer the best near-term development opportunity due to the opportunity of common ownership. Fourth, remote off-grid microgrids, representing the most operated type of microgrids globally with the smallest average capacity. Fifth, military microgrids represent a growing market segment with a focus on the integration of renewables to become independent from fuel sources. A sixth segment is utility distribution that previously was combined with community microgrids, and a seventh segment included just recently are direct current (DC) microgrids (Asmus et al., 2009; Asmus, 2019). Remote microgrids, as already outlined, is the leading market segment with 41% of capacity. This is followed by commercial/industrial microgrids (36%) and utility distribution microgrids (8%).

Institutional/Campus and Military microgrids follow with 6 and 5 per cent respectively. Apart from the recently introduced DC microgrids with less than 1%, community microgrids are the smallest segment with 4 per cent (Asmus, 2019). The most capacity from Q2 to Q4 2018 was added by utility distribution projects contributing to 40% of new capacity followed by remote projects that contributed 34% of the growth. The combined capacity of all grid-connected microgrids is larger than the capacity of remote microgrids. The current gap of 232 MW is expected to further widen to 7,346 MW by 2027, increasing the capacity of grid-connected microgrids to more than 2.7 times of remote microgrids (Wood, 2018b). Microgrid costs vary according to their segment. According to Giraldez et al. (2018) community microgrids cost an average of $2.1 million per megawatt, campus microgrids cost $3.3 million/MW, utility microgrids cost $2.6 million/MW, and commercial microgrids cost an average of $4 million/MW. The following table compares GTM's and Navigant Research's databases for their 2016 data on microgrid projects per market segment. The data varies significantly due to differences in the number of microgrid projects covered. Navigant's microgrid database covers double the amount of remote microgrid projects compared to GTM's (Giraldez et al., 2018). Table 8 provides a comparison between two of the major microgrid research firms with regard to the end-users' share of the type of microgrid.

Table 8: Comparison of Navigant Research and GTM Data for Microgrid Adoption

Type	Navigant Research (2016) by Capacity	Navigant Research (2016) by # Projects	GTM (2016) by Capacity	GTM (2016) by # Projects
Remote	29.1%	32.6%	6.8%	16.7%
Campus/Institutional	47.7%	24.7%	47.0%	40.1%
Commercial	8.1%	21.3%	26.0%	16.7%
Community	15.1%	21.3	20.2%	26.6%

Source: Giraldez et al., (2018)

4.9.6. Microgrid segments

There are six major microgrid segments: military, commercial, campus, community, utility, and remote microgrids.

a) Military microgrids

Microgrids used for military purposes only make up 5 per cent of all microgrid capacity globally but have been one of the premier use cases for the technology. The US Department of Defense (DOD), the largest consumer of energy, particularly petroleum, in the world aims to reduce its fossil fuel dependence (Hill, 2017, Walton, 2017). Microgrid implementations are one solution to achieve this and DOD spending on microgrids is expected to increase from $453 million in 2017 to $1.4 billion in 2026 (Navigant Research, 2017b). The DOD has significantly contributed to commercialising microgrids. The DOD is not the only but the largest implementor of military microgrids with other countries such as the UK, Canada, France, Russia, and China also expected to become more involved (Navigant Research, 2017c). For grid-connected military microgrids the main driver is to provide energy security in case of outages to maintain critical operations (Van Broekhoven et al., 2012). The reliability of utilities serving major military bases has been declining and remote locations have no access to the grid. In both cases Diesel generators are most commonly used to ensure energy resilience. The reliance on fossil fuels, however, can be a disadvantage with significant challenges and costs involved to organise adequate supply. Microgrids integrating renewables and storage systems are an alternative strategy to ensure resilience that has been increasingly deployed (Merchant, 2019; Mojdehi, 2018). Next to energy security, cost savings and the implementation of renewable energy sources are further drivers to adopt military microgrids (Black & Veatch, 2019). Reducing the environmental impact of military operations is a significant factor. In the United States, the 'Smart Power Infrastructure Demonstration for Energy Reliability and Security' (SPIDERS) programme has the purpose to integrate microgrids in military bases to ensure power security (Stamp, 2012). The initiative uses new solar PV and energy storage and readily available diesel backup generators to support the loads of the entire base (Aram, 2017; Hirsch et al., 2018).

b) Commercial/industrial microgrids

Commercial and industrial (C&I) microgrids are expected to be the fastest growing and most innovative market segment in the coming years (Asmus, 2019). Historically C&I microgrids have the highest percentage of legacy assets but new assets in form of renewable energy generation are being added (Wood, 2018b). C&I microgrids often use existing diesel generators which make up the largest share of integrated DER technologies, but energy storage, CHP, and solar PV are increasingly adopted (Giraldez et al., 2018). The global capacity of C&I microgrids is projected to grow from 448.3 MW in 2017 to 5,389.1 MW annually by 2026 (Navigant Research, 2017d). The segment had, however, issues to gain traction as C&I microgrids were often not considered as an alternative to traditional backup generation, had an unsatisfactory return on investment, and no compelling business models existed. The lack of standards has also limited C&I projects globally (Navigant Research, 2017d; Aram, 2017). Novel business models such as power purchase agreements (PPAs) that allow customers to adopt C&I microgrids without capital expenditure have led to segment growth (Aram, 2017). C&I microgrids have benefitted from the diffusion of other microgrid segments and applications as this developed has increased the acceptance of the technology. The C&I microgrid segment benefits from clients with substantial investment capital interested in innovative business models. The reliability of microgrids is a highly valued aspect for C&I clients increasing their willingness to invest. The general declining cost trends for renewable energy technologies such as solar PV, batteries, and inverters as well as improved regulations make C&I microgrids an increasingly attractive investment (Navigant Research, 2017d). A major challenge the segment faces are the exceptionally low electricity rates offered to industrial clients decreasing the motivation to invest into alternatives. The intense competition for capital expenditures is a further barrier (Navigant Research, 2017d).

c) Campus/institutional microgrids

Next to military installations, universities and research facilities have also been among the first adopters of microgrids (Tweed, 2014). A major driver for research related microgrid applications has been power security. Universities have several critical facilities such as research labs that require energy backup in case the main grid faces power outages. It has also been shown that energy security is regarded as a positive characteristic in choosing universities (Aram, 2017). Another driver for universities to install microgrids is to make campuses more environmentally friendly and to meet the ambitious sustainability targets. A third driver is to use microgrids as research sites and for educational purposes. Some of the most advances microgrids have been installed at university campuses. Examples are the University of California, San Diego, Princeton University, and the University of Texas at Austin (Wood, 2017). University campuses and other institutions consume large quantities of energy for cooling, heating, and power making them particularly suited for microgrid installations (Aram, 2017). Combined heat and power (CHP) and combined cooling, heat, and power (CCHP) microgrids have proven as a successful model and dominates generation capacity for this segment (Giraldez et al., 2018; Hirsch et al. 2018; Wood, 2017). The existing electric and thermal infrastructure of universities with limited interconnection points with the utility reduces technical complexity and costs of microgrid projects. Existing campus microgrids are offering among the largest capacities of all segments (Hirsch et al. 2018; Wood, 2017). Campus microgrids are most often deployed in North America which is the region with the highest annual capacity and revenue. Total capacity in North America alone is expected to increase more than fivefold from 219 MW in 2015 to 1200 MW in 2024 (Aram, 2017).

d) Community and building-integrated microgrids

Community microgrids are often government supported programs to provide energy resilience in case of weather-related outages (Aram, 2017). Extreme weather events causing grid failures and the consequential loss of power to critical infrastructure lead to substantial losses and costs. An infamous example that highlights the vulnerability of urban communities was Superstorm Sandy that hit the North-Eastern United States in 2012 and affected more than 8.5 million people (Mukherjee et al., 2018) causing up to $25 billion in lost business activity (Webley, 2012). The main driver for community microgrids is therefore to reduce the dependence on utility-supplied energy to improve community resilience followed by the aim to lower carbon emission rates (Yuan et al., 2017). Power supply reliability also helps communities to attract companies that value resilience and the constant availability of critical infrastructure and public services. This in combination with the potential for reduced energy costs can strengthen a community’s economy (Advisian, 2019). Community microgrids currently represents the smallest segment with limited growth potential (Asmus, 2019). The segment faces numerous regulatory challenges such as ownership of the community microgrid, third-party generation participation, how to recover investments, and inclusion in the utility rate case (Bahramirad et al., 2015). Community microgrids involve several participants and electricity off-takers which causes technical and financial challenges. The numerous stakeholders represent a broad spectrum (hospitals, individual households, grocery stores etc.) which complicates the adoption of a suitable business model. There are, however, ongoing efforts by governments to reduce these barriers (Aram, 2017). Further, since community microgrids are built upon the existing utility distribution network, they need the support of utilities to ensure a sustainable deployment (Bahramirad et al., 2015). Communities often integrate existing diesel back-up and natural gas generators into new microgrid projects (Giraldez et al., 2018). Different approaches to residential microgrid have been discussed in the literature with the optimal level of microgrid aggregation being a central topic (Hirsch et al., 2018). One option is to deploy microgrid technology at the individual household level (Sechilariu et al., 2013), representing a fully decentralized approach. The advantages of this building-integrated microgrid approach include full customer control over DERs and that most changes necessary to add microgrid technology occur behind the utility meter. The latter results into less legal and regulatory barriers as opposed to large community microgrids that integrate households with no main grid connection (Hirsch et al., 2018; Sechilariu et al., 2013). The disadvantages of the building-integrated approach are its inability to capture full economies of scale and its low load and generation diversity. Community microgrids that rely on shared DERs and loads can be more cost efficient (Hirsch et al., 2018). In general, larger shared distributed generation units achieve superior economies of scale over micro-sources in individual households. There is a significant connection cost involved per DG unit to the utility and having a cluster of micro-sources behind the meter as part of a community microgrid reduced the overall cost of the system (Lasseter, 2007). Another promising residential microgrid concept integrates PV systems, electric vehicle (EV) batteries, and energy storage systems (ESS). The PV system charges the ESS during daylight reducing over-voltages and at night the ESS charges the EV batteries reducing under-voltages (Rodriguez-Diaz et al., 2015). This reduces regulatory barriers as feed-in tariff policies are not required due to limited power exchange with the main electricity grid (Hirsch et al., 2018).

e) Utility microgrids

Utilities are increasingly exploring microgrids as potential revenue streams and options to upgrade grid infrastructure to meet the challenges of the current grid transformation. They are in the difficult position of maintaining centralized generation and distribution infrastructure while integrating an increasing amount of distributed energy resources (Navigant Research, 2018a). Several utilities in the US have microgrid projects. Aram (2017) lists the 'San Diego Gas & Electric's Borrego Springs

Microgrid', 'Duke Energy's Mount Holly Microgrid', and the 'National Grid's Potsdam Microgrid' as examples. Microgrids are also beneficial for utilities by providing extra capacities during peak power demand and more flexibility to undertake system repairs without affecting end-customers (Kroposki et al., 2008). The increasing global interest, installed capacity, and regulatory support for microgrids has contributed to utilities investigating the role of microgrids in the energy market (Navigant Research, 2018b).

f) Remote microgrids

Remote microgrids represent the most mature and largest of all microgrid segments. They are characterised by constant operation in island mode as no connection to utilities exists, decentralized control systems, limited maximum power use, and looser power quality requirements compared to industrial microgrids (Majumder, 2013). The most common form of distributed energy resources used for remote microgrids are still diesel generators due to their affordability (Pelland et al., 2012). However, renewable energy and energy storage capacity is continuously increasing (Giraldez et al., 2018). PV systems and less often also wind turbines are increasingly integrated into diesel-based remote microgrids, so called hybrid microgrids, to reduce operational costs and diversify generation (Nema et al., 2009; Shakya et al., 2016). A major driver for remote microgrids is the low electrification rate in some regions (Illindala et al., 2007; Williams et al., 2015). Remote microgrids deployed in electrically underdeveloped regions benefit from the same technological advancements that drive the energy transition in developed markets resulting in smarter microgrids for these regions (Hirsch et al., 2019). A major issue that reduces the profitability of remote microgrids is theft (ESMAP, 2000). The most common form of theft are unauthorized connections to the remote microgrid's distribution line and meter manipulations (Buevich et al., 2014). Hybrid microgrids are designed to reduce overall fuel consumption. Diesel generators only operate at their best fuel efficiency when they operate at high loading. This is often not the case in hybrid microgrids as peak load requirements determine the size of generators and PV or wind additions further reduce the average load. This leads to suboptimal fuel efficiency due to generators operating at low loading for which they are not designed (Nayar, 2012). This may cause an increase, as opposed to a reduction, in fuel consumption of a PV-diesel microgrid (Chalise et al., 2013). In order to prevent this, storage systems need to be installed which act either as a source to support the generator in meeting load requirements or as a load to use the generator at full capacity (Chalise et al., 2016; Pelland et al., 2012).

5. DISCUSSION AND CONCLUSIONS

This industry study raises theoretical questions on multiple levels and provides several opportunities for further research. First, on a general level, future studies are encouraged to examine the wide-reaching societal implications of decentralized energy and microgrids. This work provides scholars with a useful foundation to examine policy implications of integrating distributed energy resources, renewable energy, and microgrids into the existing power infrastructure. Policy makers should investigate initiatives to support this decentralization process. This review demonstrates the potential for empirical studies to investigate the vast transformation the power sector is undergoing. Novel technologies such as microgrids increasingly put pressure on incumbents, challenge established structures, provide new solutions to existing while also creating new problems. Organisational scholars could apply a more technology-centred approach in studying these developments. Second, studies in the field of management could focus on the drivers and barriers of the decentralization process. This could include a cognitive perspective that investigates what influences stakeholders' interpretations of novel technologies. Third, this review highlighted the importance of complexity within emerging product markets. Increasing levels of complexity for industries and markets have far reaching consequences for participants. Future studies are encouraged to investigate the role of complexity in shaping actors' assumptions, expectations, and knowledge of a technology. The rising complexity of the electricity industry with its structural changes provides great opportunities for future studies in the fields of policy and organisation science to investigate challenges and wide-reaching impacts for society.

This review of the electricity industry and microgrid market integrated the historical context of power networks with insights on microgrid technology development. The study emphasised the importance of microgrid technologies and related innovations for the successful transition to an energy system with sustainable generation and supply. I contribute to the existing literature on power systems and the microgrid market by relying on a unique combination of data sources to form an in-depth review of the microgrid market situated within the historical context of the power sector and its transitions. A further aim was to introduce microgrids and their importance for the current energy transition to the wider research community outside the technical literature on power systems. Microgrids might seem to be niche applications from afar but what this review has shown is their central role in enabling a transition to a more decentralized grid architecture and the successful integration of more renewable energy sources.

PAPER TWO

TECHNOLOGICAL FRAMES AND COMPLEXITY DIFFERENTIALS: A STUDY OF THE MICROGRID INDUSTRY AND ITS STANDARDIZATION EFFORTS

ABSTRACT

Technological frames guide the sensemaking of individuals with regard to new products and thus influence the evolution of product markets. But what influences the transformation of technological frames themselves? This two-year qualitative study of the emerging microgrid market examines how technological frames are shaped with a focus on the role of complexity as an important factor driving this process. This study offers several theoretical insights: By introducing the concept of complexity differentials to the literature on technological frames I show the importance of aligning frame complexity with market and technology complexity. The concept of complexity differentials describes the asymmetrical relationship in complexity between a technology and its environment. My argument contributes to the literature on cognitive frames and strategic management as I highlight the role of technological frames on market trajectories. In introducing the concept of complexity differentials, as perceived by actors, I offer an alternative explanation for frame transformation due to frame instability caused by increasing complexity differentials between the frame, technology, and the environment.

Keywords:

Technological frames; Complexity differentials; Microgrids; Distributed energy systems

INTRODUCTION

The electric grid faces increasing challenges due to severe weather events causing outages, unsustainable power generation based on resource exploitation, an aging infrastructure, and inefficiencies due to long distance transmission lines (Amin, 2008; Barrett, 2016; Mukherjee et al., 2018). Among a collective societal effort, it needs the adoption of technological innovations to address these challenges. Individuals hold and shape "technological frames" (Orlikowski & Gash, 1994) related to product innovations (Seidel et al., 2020). This paper explores how collective technological frames transform in relation to changing market conditions. Technological frames are a sub-type of cognitive frames. Goffman (1986: 21) describes cognitive frames as 'schemata of interpretation' that provide actors with a lens through which the complexity and ambiguity of the environment can be reduced. This allows actors to selectively organize and interpret signals and thus shapes their sensemaking and decision-making processes (Dutton & Jackson, 1987; Kaplan, 2008a; Kaplan & Tripsas, 2008). Actors not only deploy frames to make sense of complex situations, but also to shape outcomes (Creed et al., 2002). For example, actors attempt to establish the legitimacy of their frames to influence the sensemaking of others while validating their own legitimacy as claims-makers (Benford & Snow, 2000; Kaplan, 2008a; Lounsbury & Glynn, 2001). Cognitive framing is based on past learning and categorization (Mervis & Rosch, 1981) and may result in a confirmatory bias that shifts the focus from inconsistent signals to those which align to existing frames (Palich & Bagby, 1995). Prior research illustrates how framing can lead to sub-optimal decision-making based on inaccurate information, stereotypic thinking, or the non-consideration of potentially important information leading to unintended outcomes (Dean & Sharfman, 1996; Hahn et al., 2014; Walsh, 1995).

The literature has examined different underlying mechanisms leading to shifts and transformations of cognitive frames. The majority of mechanisms are related to integrating new information, learning processes, and the conflicts and tensions between existing frames. 'Assimilation' is the process by which new environmental information is integrated into existing frames. 'Accommodation' describes the process by which existing frames are altered as new information does no longer fit into established categories (El Sawy & Pauchant, 1988; Flavell, 1966). Further mechanisms related to the learning process are: 'accretion' which describes the process by which novel knowledge is integrated into existing frames, 'structuring' which refers to the process of new frame formation, and 'tuning' which is the ongoing process of modifying and integrating existing frames in order to improve their fit to the environment they describe (El Sawy & Pauchant, 1988; Norman, 1982). El Sawy and Pauchant (1988) emphasised more than three decades ago that the processes through which cognitive frames shift need to be better understood. Frame transformation also becomes necessary when frames "may not resonate with, and on occasion may even appear antithetical to, conventional lifestyles or rituals and extant interpretive frames" (Snow et al., 1986: 473). However, beyond these insights, we have very little understanding of the frame transformation process, particularly for technological frames. A technological frame influences the interpretation of what a technology entails, provides guidance whether it is useful (Kaplan & Tripsas, 2008: 791), and facilitates categorization and the selection of relevant performance criteria (Benner & Tripsas, 2012). Technological frames deeply influence stakeholders' perception of technology, their related thought processes, problem solving, and strategy formulation (Klein & Kleinmann, 2002). Technological frames also shape the actors' sensemaking of a technology with respect to how the technology is categorized in relation to other technologies and how its performance is evaluated (Kaplan & Tripsas, 2008).

Stable technological frames, that are widely shared and extended across space, are required for both the enactment of a product market by stakeholders and its existence (Seidel et al., 2020). Frames with a high stability are thus less likely to be transformed or replaced. The acknowledged importance of cognitive frames in general and technological frames in particular makes it important to understand where and how such frames are shaped and what factors influence their sustainability, stability, and reliability. This study therefore aims to address the following research question: How do frames evolve in the context of complex emerging technologies? This paper contributes to this question by analysing the alignment over time of technological frames, the product/technology, and market complexity. The findings show how these types of complexities, as perceived by industry actors, shape the evolutions of technological frames. In particular, I find that misalignment of technological frame complexity with the complexity of the environment may trigger efforts at collective frame transformation. I propose the concept of *complexity differentials* as a valuable addition to the thinking on technological frames.

CONCEPTUAL BACKGROUND

Orlikowski and Gash (1992; 1994) introduced the concept of technological frames to address issues directly related to technologies that are not sufficiently covered in social cognition studies. The authors (1994: 178) define technological frames as the "subsets of members' organizational frames that concern the assumptions, expectations, and knowledge they use to understand technology in organizations. This includes not only the nature and role of the technology itself, but the specific conditions, applications, and consequences of that technology in particular contexts". Technological frames guide stakeholders as they direct perceptions and interpretations of the value, function, and role of a technology (Gash & Orlikowski, 1991) and thus influence market development (Seidel et al., 2020). Identical technologies can therefore be viewed differently depending on the frame applied (Pinch & Bijker, 1984). They offer a useful analytic perspective for explaining and anticipating actions related to a novel technology that are "not easily obtained with other theoretical lenses" (Orlikowski & Gash, 1994: 174).

Technical choices to either invest, support, or adopt a particular technology are influenced by the technological frame that is applied, affecting a technology's evolution and legitimacy (Kaplan & Tripsas, 2008). Prior studies have shown that technological frames are shaped in interactions among stakeholders (producers, consumers, and the media). Henderson (1995) found that inaccurate shared beliefs of actors within an industry about the projected progress of technologies led to significant flaws in performance projections for firms operating in the industry. Shared beliefs of actors in emerging industries with novel technologies and users are particularly influential as decision-makers lack required industry data (Benner, 2010). Cognitive frames cannot solely be regarded as an individual-level concept. Individuals may hold contrasting frames, but collective technological frames may emerge (Seidel, 2020). Widely shared technological frames lead to common views and interpretations that may inform collective action (Weick et al., 2005).

Several studies have shown the contribution of traditional media in shaping technological frames through influencing the legitimacy of producers or creating product categorisations (Navis & Glynn, 2010; Rao, 1994). Social media such as technology blogs also shape technological frames (Seidel et al., 2020). Rosa and colleagues (1999) found that magazines and industry trade journals shaped collective technological frames related to novel product adoptions within the then emerging market of minivans.

Issues may arise when outdated technological frames are applied during times of technological change, as it has been found with top management teams (Tripsas & Gavetti, 2000). Technical experts are particularly resistant to adopt updated frames and may miss critical information of new technologies as a consequence (Cohen & Tripsas, 2018; Henderson & Clark, 1990; Starbuck, 1996). Those with a profound understanding of an old technology may be the most resistant to information contradicting their beliefs (Starbuck, 1996). It can be concluded that outdated technological frames held by experts are particularly resistant to change and may lead to misinterpretations of novel technologies and sub-optimal decisions.

Technology and complexity

Building on the definition of technology as a "set of pieces of knowledge" (Dosi, 1982:151), the complexity of the world's knowledge has been continuously rising (Aunger, 2010:776; Mewes & Broekel, 2020). Scholars have increasingly acknowledged the importance of studying complexity (Simon, 1996: 181) but no generally accepted definition has been established (Singh, 1997: 340). For the purpose of this study, systems and technologies are defined as complex when "a large number of parts…interact in a non-simple way" (Simon, 1962: 468). In other words, the complexity of a system depends on both the number of distinct components and their interconnections (Simon, 1962). A rise in components and interconnections leads to higher levels of complexity, making complexity a "matter of degree" (Simon, 1997: 358). Complexity is generated due to the large number of components that limits observers' ability to understand the structure as a whole and the difficulty in predicting the outcome of interactions on system performance (Ethiraj & Levinthal, 2004: 407). The level of complexity of any given structure is significantly affected by how it is described and represented by observers (Simon, 1962: 481). Complexity therefore also depends on the "eye of the beholder" (1976: 508). Rothwell (2011: 562) also emphasises that "technological complexity is subjective and must (also) be understood in terms of the user". Increasing complexity requires higher information-processing capabilities reducing the ability of decision-makers to rationally account for all relevant factors (March & Simon, 1958) ultimately increasing the probability for decision errors (Levinthal, 1997). Decision-makers need to engage in time consuming (Raaijmakers et al., 2015), effortful problem-solving (Walsh, 1995), and sensemaking (Weick, 1995) activities when they face complexity.

I refer to complex systems, such as microgrids, as technology products in line with research on complex products and systems (CoPS). CoPS are defined as "high cost, high technology goods made in projects and small batches" (Hobday, 1998: 692). They are "highly customised, engineering-intensive goods which often require several producers to work together simultaneously" (ibid: 689).

Central to Simon's (1962) work on complex systems is the view that those that successfully develop possess a hierarchical nested structure among subsystems and are characterised by near-decomposability. The grouping of system components into a lower number of subsystems offers a possibility for observers to reduce and manage complexity of systems (Simon, 2000: 9; Langlois, 2002: 20). Simon (2001: 10-11) calls this 'near-decomposability' which describes systems with existing subsystems that show a higher number of connections and interactions within than across subsystems. In other words, the frequency of interactions within subsystems outweighs the frequency that occurs between subsystems (Murmann & Frenken, 2006). Near-decomposability and a hierarchical structure facilitate the process by which systems become visible and understandable to the observer (Simon, 1996: 207). Nearly decomposable systems have advantages over non-decomposable systems as they are easier formed and can evolve and improve their performance at a faster rate (Simon, 2001). Near-decomposability describes modularity as the concept of decoupling complex systems into subsystems that operate nearly independently of each other (Simon, 1962; Andriani & Carignani, 2014).

Luhmann (1978: 97) states that within complex systems there needs to be some selectivity in the connections between elements as not all mathematically possible links can be realised. As a consequence, there is no full interdependence of elements within a complex system. It can thus also be concluded that complex systems are characterised by their high number of elements that requires a selection in how they are connected (ibid).

Singh (1997) found that high technological complexity increases the risk of business failure compared to businesses that commercialise low-complexity technologies. The author argued that this higher failure rate can be explained by greater competency demands and higher costs. Technological complexity poses significant challenges for businesses and markets in commercialising products. Adoption issues are often related to concepts such as newness, diversity, or sophistication of technology but empirical evidence shows that complexity might be the major barrier for technology commercialisation (Singh, 1997). Technological complexity between products is difficult to measure on an absolute scale as it is highly context specific (Singh, 1997: 341). This difficulty of non-practical comparisons leads most studies to use relative measures that compare the complexity between closely related technologies (ibid.).

This study draws on different types of complexities to form the complexity differential construct that is utilised as a mechanism driving frame transformation. In the following paragraphs the technological frame, industry/market, and technology/system complexities are introduced before focusing on complexity differentials.

Technological frame complexity

Technological frames can also be characterised by different degrees of complexity. The level of differentiation and integration has been one method to describe frame complexity (Bartunek et al., 1983: 274; Gröschl et al., 2019: 743). Differentiation refers to the number of elements within a frame and integration refers to the degree of interconnectedness among these elements (Gröschl et al., 2019; Walsh, 1995). Accordingly, a technological frame increases in complexity when its number of frame elements and the interdependence between them increase. Weick (1979) advised decision-makers to observe and understand events from more than one perspective as problems may have more than one cause. Weick argues that most individuals hold narrow cognitive frames that limit the variety of interpretations and understandings of situations. This leads to ineffective decision-making as many situations have a higher level of complexity that can be interpreted in more than one way. The aim therefore is to match the variety in their cognitive frames with the variety in the situation in order to allow for the best possible decisions and problem solving (Bartunek et al., 1983; Weick, 1979). A higher complexity of technological frames leads decision makers to consider a broader spectrum of available information as well as other stakeholders' opinions (Hahn et al., 2014; Wong et al., 2011). The complexity of the technological frame itself is of high significance in determining complexity differentials.

Appropriate level of complexity

Several scholars (e.g. Ashby 1957; Calori et al., 1994; Weick, 1979) have argued that the relationship between complexity and firm performance is not linear but curvilinear with moderate complexity levels being optimal as either too little or too extreme complexity will reduce profitability. From this stream of research, it can thus be concluded that there is an optimal level of complexity (McNamara et al., 2002). This suggests that there might be also an optimum level for complexity differentials. Ashby's law of requisite variety (1956; 1957) states that a stable system that can cope with the challenges of its environment has a variety of responses that at least match the variety of the environment. In other words, the system needs to have sufficient complexity in order to be able to handle the complexity of the environment: "only variety…can force down variety" (Ashby, 1957: 207). Weick (1979) later confirmed this view on complexity matching.

Weick (1979: 261) emphasises the importance of complication for decision-makers in order to cope with environmental complexity. Voyer (1993) found a strong positive relationship between the complexity of knowledge structures and firm performance. He concluded from his study of the pharmaceutical industry that decision-makers with more complex mental models have the ability to grasp more pre-existing dimensions about their industry and have the potential to better understand the behaviours of competitors by utilising more dimensions. Schneier (1979) connects the complexity of decision-makers knowledge structure to the ability to deal with inconsistent and ambiguous information. A certain degree of complexity is essential for business processes to be able to cope with environmental complexity (Flood & Carson, 1993: 23; Jackson, 2000: 73). However, too much complexity hinders standardization efforts (Barki & Pinsonneault, 2005; Mani et al. 2010) with increasing effort required the more complex the business process is (Schäfermeyer et al., 2012). In cases of high environmental complexity that cannot be reduced, business processes need to mirror this complexity, decreasing the feasibility for standardization (Lillrank, 2003). Complexity can be advantageous and lead to a competitive advantage when it can be controlled and managed. However, unwanted complexity may hinder the development of an organisation (Stratechi, 2020). Newman (2009) identified distrust for standardization as one of the key drivers of complexity. He finds that designers and engineers do see constrains and limitations in standardization and modularization as they are viewed as barriers to the creative development of novel products. The author argues that modularization aims to manage variety and not to limit it and that standardization enables product improvements through incorporating best practices.

The importance of customized goods and services has increased for most industrial sectors over recent years. The increase in product variety and resulting component diversity has led to a rise in complexity. There is the general need for firms to control product complexity and costs while allowing for customization and maintaining quality standards (Franke et al., 2002; Thumm & Goehlich, 2015). One way to achieve such a robust product architecture is through standardization using a modularization strategy (Dai & Scott, 2007; Hanafy & Eimaraghy, 2013). Mass customization is a strategy that allows for custom products while controlling for costs and complexity (Schöning, 2007). It thus represents a compromise between mass production and individual customization. Robust business models manage complexity by finding a balance between as much variety as demanded and as little variety as possible (Thuesen & Hvam, 2013). Thus, the literature suggests that both complexity and complexity differentials have optimum levels. The complexity of a technological frame as well as the difference of the frame's complexity relative to the technology and market complexities are likely drivers of a frame's instability. Table 1 provides a summary of complexity definitions at various levels.

Table 1: Complexity Definitions

	Complexity Definition
Industry/ Market	• the extent of competitiveness and heterogeneity of a firm's operating environment (Aldrich, 1979; Dess & Beard, 1984) • the extent of competition and entrepreneurial activity (Khandwalla, 1973; Starbuck, 1976; Williamson, 1965) • the number, diversity, and distribution of task-environment elements (Aldrich, 1979; Dess & Beard, 1984)
System/ Technology	• "a large number of parts…interact in a non-simple way" (Simon, 1962: 468). • change in one unit or component requires the change in many other units or components (Larsen et al., 2013) • "an applied system whose components have multiple interactions and constitute a non-decomposable whole" (Singh, 1997: 340) • multiple interactions between components within and across subsystems at various hierarchical levels which lead to non-simple relationships (Simon, 1969)
Frame	• frame complexity refers to the degree of differentiation and integration (Bartunek et al., 1983: 274; In: Gröschl et al., 2019: 743) • technological frame complexity increases when the number of frame elements and the interdependence between them increase (Luhmann, 1975, Rothwell, 2011; Schneider et al., 2016)

Standardization and complexity

A standard can be regarded as striking a balance between user requirements, technological possibilities, and constraints imposed by governments (Germon, 1986; Tassey, 2000). Standardization is the process by which this conformity is achieved. Standards have a significant effect on R&D, production, and the diffusion rate of technologies and as such influence the overall market structure and productivity (Tassey, 2000). Microgrid projects are often highly customized, requiring expensive one-off engineering solutions and often depend on government subsidies as a consequence (Asmus et al., 2018).

Ahuja and Novelli (2017) identified standardization as one key mechanism through which firms can deal with higher complexity. Standardization reduces complexity by limiting changes in product features and interconnections between product features. Benefits of standardization are improved safety and security, cost and quality control, reduced complexity, and faster provisioning (von Faber, 2014). Standardization enables cost reductions through scaling effects and quality improvements through more time devoted to solution optimization. Security and safety of technologies across applications and countries have increased in importance. Extensive complexity makes it difficult to maintain high levels of security and thus needs to be reduced. Standardization is one available tool to reduce complexity and to enable the same high level of security globally (von Faber, 2014). Standardization increases both quality and security up to a certain degree when it becomes costly and finally damaging due to decreasing flexibility and attention. Many organisations face increasing complexity as a result from a rising number and diversity of elements and interconnections within business relationships such as from customized products and services (Blecker et al., 2005; In: Schäfermeyer et al., 2012). Business processes with high complexity are more difficult and costly to standardize (Rosenkranz et al., 2010) and hinder problem-solving activities (Mani et al., 2010).

Complexity differentials

Central to this study is the concept of complexity differentials as a mechanism influencing frame stability and thus driving the technological frame transformation and replacement. According to social system theory the environment is necessarily more complex than the systems it contains (Luhmann, 1995). Schneider et al. (2016), drawing on social systems theory, found that systems need to increase their complexity when the difference between their own and the complexity of the environment becomes too large. This difference is referred to as the complexity differential. A too large complexity differential reduces the ability of organisations to make informed decisions (Daft & Lengel, 1986) and thus to respond to environmental demands sufficiently (Schneider et al., 2016). The authors argue that organisations react to overwhelming complexity by generating complexity themselves to reduce the complexity differential relative to their environment. The concept of complexity differentials has been developed within social systems theory, which provides a "complexity-based sociological perspective on how social systems respond to challenges in their environment" (Schneider et al., 2016:2). According to social system theory, complexity enforces selectivity, a process that reduces complexity through supporting systems that are less complex than their environment. The resulting asymmetrical relationship in complexity between the system and its environment is referred to as the complexity differential (Knodt, 1995). Systems cannot implement all available information of their environment and are thus inevitably less complex than their environment (Luhmann, 1995; Seidl & Becker, 2006). Complexity differentials are essential to prevent undifferentiated chaos (Knodt, 1995). However, the differential cannot become too large to prevent systems from becoming unable to acquire or process the information required for optimal decision-making (Daft & Lengel, 1986) and to respond to environmental challenges (Schneider et al., 2016). In order to remain valid and survive, a system that faces an increasing complexity differential therefore has to "increase its own complexity relative to that of its environment" (Schneider et al. 2016: 2).

SETTING

The rising complexity of the electric power system

There has been a general trend towards greater complexity of technological innovations. This has been shown by the increase of complex technologies of the 30 most valuable world goods exports from 43% in 1970 to 84% in 1996 (Kash & Rycroft, 2002; UN, 1975; 1996). In line with this trend, already complex energy systems (Afgan & Carvalho, 2008; Babrowski et al., 2014) are increasingly becoming more complex (Fang et al., 2020; Shiwen et al., 2017) with higher degrees of decentralization and integration of more diverse energy sources such as renewable energy (Pfenninger et al., 2014). In addition, business model complexity within the power sector has also increased (Hall & Roelich, 2016). One explanation for this rise in complexity is the vast transformation the electric power system is undergoing which is driven by a transition towards distributed energy resources (DERs) which often include carbon-free generating sources to address environmental concerns. The traditional power grid has a centralized structure with large generation plants from where the electricity is distributed via transmission and distribution lines to consumers. This structure is slowly shifting towards decentralized generation with users becoming prosumers by generating their own electricity and feeding unused electricity back into the grid, a process described as bidirectional electricity flows (Fang et al., 2012). The energy sector is therefore moving from centralized generation with unidirectional electricity flows towards decentralized generation with bidirectional electricity flows, which is increasing market and technological complexity. Figure A1 shows an illustration of this transformation and Table A3 provides evidence for the growing complexity of the energy industry.

Microgrids

Microgrids represent an emerging and scalable technology to support the decentralization process and the transition from fossil fuels to clean energy while offering a solution to reduce energy poverty and meet the growing global electricity demand (Armstrong et al., 2016). Since Bob Lasseter coined the microgrid term in 2001 (Hubbuch, 2019), various definitions of microgrids have emerged (Farhangi, 2016; Olivares et al., 2014). In general, a microgrid refers to an "integrated energy system consisting of distributed energy resources (such as generators and storage systems) and multiple electrical loads operating as a single, autonomous grid either in parallel to or 'islanded' from the existing utility power grid" (Asmus et al., 2009). A microgrid can therefore function irrespective of whether it is connected or disconnected to the grid. For more technical definitions, please see Table 2. Microgrids, like many products in the electricity industry (Enberg et al., 2010), are highly complex artifacts.

Over the last decade the interest in microgrids has been increasing around the world (Radhakrishnan et al., 2019). Microgrids have several benefits including improved energy efficiency, reduced emissions by integrating renewable energy sources, reduced energy consumption, improved power supply reliability and network stability (Marnay et al. 2015a). However, microgrids, being highly complex projects, face numerous challenges in their diffusion process with the lack of standardization being a major factor (Lopes et al., 2013).

Table 2: Microgrid Definitions

Definition	Reference
"Electricity distribution systems containing loads and distributed energy resources, such as distributed generators, storage devices, or controllable loads, that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded"	CIGRÉ Working Group, In: Marnay et al., 2015a
"A group of interconnected loads and distributed energy resources (DER) within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected and island mode"	US Department of Energy (DOE), 2012

Microgrids, complexity, and standardization

In line with many infrastructure projects, the majority of larger and more complex microgrids have been custom engineered (Hirschbold, 2019). Large microgrid projects are also likely to depend on some degree of customization in the future despite significant progress in standardization efforts. Further, manufacturers and service providers serving the microgrid value chain are fragmented with produced components often not allowing for economies of scale complicating standardization efforts (van den Berg et al., 2016). The high complexity of advanced microgrids integrating numerous technologies with complex interactions requires individual optimisation (Stadler & Nasle, 2019). Large infrastructure developers as well as consultants benefitted from highly customized microgrids, but end customers, utilities, and other project developers require higher degrees of standardization (Cherian & Asmus, 2016).

One central component of each microgrid is the control system. The basic functions of microgrid controllers are to transition the system from grid-connected to an islanded mode and to balance load and generation (Razeghi et al., 2018). Advanced controllers possess predictive analytics capabilities by, for instance, analysing weather data to predict renewable energy resources availability and use real-time pricing data to optimise the distributed energy resources mix (Microgrid Knowledge, 2019). The shift from basic to advanced controllers also reflects the higher levels of complexity of the technology. Table A4 provides representative evidence for the rising complexity of microgrids.

The microgrid market faces issues related to a lack of standardization and regulations (Lopes et al., 2013). Microgrid projects are often highly customized, requiring expensive one-off engineering solutions and often depend on government subsidies as a consequence (Asmus et al., 2018). Standards are essential for microgrids to become an established part of the future energy system. Without standards microgrids could become prematurely obsolete or may cause security and safety issues. Also, a lack of standards may hinder future innovations and prevent the creation of a guiding framework for the development of renewable energy and related technologies (Daghrour & Al-Rhia, 2019). Further, only with standards sufficient economies of scale and scope can be established to create a competitive microgrid market and thus increase diffusion rates and benefits to the customer (Berker & Throndsen, 2017; NSTC, 2011). Standards, when used properly, are tools of industrial progress that ensure quality through consistency (Hall, 1986). Due to the complexity of microgrid systems there are both de facto and de jure standards involved. De jure standards for microgrids are legally enforced by recognised standards organisations such as the 'Institute of Electrical and Electronics Engineers (IEEE)', the 'International Electrotechnical Commission (IEC)' or the 'European Committee for Electrotechnical Standardization (CENELEC)'. An example for de-facto standards are existing communication protocols (Cintuglu et al., 2015) that achieved a dominant position within the microgrid market.

Microgrid developers face the challenge of making hardware and software components interoperable across distributed energy resources, storage and control systems, and user application technologies (van den Berg et al., 2016). Over recent years modular approaches to microgrids have contributed to the adopt- and adaptability of microgrids by facilitating the design, installation, and maintenance of microgrids. In general, modularization refers to the break-down of larger systems into smaller modules. The reduced costs of individual modules encourage competition (Baldwin & Clark, 2006). Applying modularization to microgrids means to divide large microgrid systems into smaller standardized modules (Cohn, 2017). A microgrid with a modular architecture may be expanded to achieve larger capacities by integrating additional modules (Lin et al., 2014). The modularity facilitates the ability to make microgrids plug-and-play, reduces the complexity of the required control systems, and simplifies the installation for utility firms (Cohn, 2017). The modular architecture of such microgrids with more standardized components have cost-advantages over custom-engineered projects and benefit from improved reliability (Asmus et al., 2018). A specific example of modular microgrids are container microgrids, defined as modular microgrids that fit inside a single shipping container (Francklyn, 2019).

Barriers for microgrid market development

Soshinskaya et al. (2014), in their review of thirteen case studies, found four major categories of microgrid implementation barriers: technological issues, regulatory barriers, high costs, and stakeholder cooperation. These four categories are often intertwined and are all related to the lack of standardization. The high costs related to still expensive distributed energy and storage technologies reduce the return on investment and are thus hindering market growth (Soshinskaya et al., 2014). Further barriers for market growth are technical and regulatory issues related to the bi-directional power flow between the microgrid and grid network, power trading, control, and operation of the microgrid (Bellido et al., 2018; Soshinskaya et al., 2014). Stakeholder cooperation can be a barrier when the incorporation of prosumers leads to further complexity due to conflicting interests in the microgrid implementation and operation (Soshinskaya et al., 2014). Stadler and Naslé (2019) in their recent article argued that costly non-standardized approaches for microgrid planning result from treating every system as being unique. In addition to the high costs of this individual approach to planning, it prevents comparisons between projects and hinders market growth. Microgrid projects have had high failure rates also due to excessive non-standardized feasibility studies that increase upfront costs and discourage investors (Cherian & Asmus, 2016).

Microgrid business models

The microgrid market has a broad spectrum of business models reaching from simple to highly complex. The level of complexity of the single user model is one of the lowest as there are not multiple end-users but loads are supplied to a single consumer (Castro, 2020) such as a hospital. The utility rate base model involves a utility firm that owns and operates the microgrid. The users of the microgrid are charged by the utility but are not responsible for investment and operational costs. The main purpose for microgrids deployed by utilities is the integration of distributed energy resources and/or to reduce peak demand to improve the reliability and resilience of the distribution system controlled by the utility. It is more complex than the single user model as regulations change from country to country with regard to ownership of generation assets by distribution utilities (Asmus & Lawrence, 2016; Castro, 2020). The hybrid model is a combined ownership of assets by the utility and participants. Participants are therefore only partially responsible for the investment and operational costs (Castro, 2020). The multi-user model involves a third party that builds, operates, and maintains the microgrid serving several participants who pay a regular fee for the service. It can be agreed that assets are transferred to participants once the third party recovered its investment costs (Castro, 2020). Energy as a Service (EaaS) business models represent the highest level of complexity and innovation. Third party providers finance, operate, and maintain the microgrid and advise end-users on energy management. For these services customers pay a fee over an agreed period (Castro, 2020). More complex business models such as multi-user and EaaS can involve peer-to-peer energy trading, which allows one or several participants of the same microgrid to trade energy with each other using blockchain technology (Castro, 2020). Figure A2 illustrates the shift towards more complex microgrid business models.

DATA AND METHODS

Microgrids were chosen for two reasons. First, they are complex products that are systemic and comprise components that interact in non-simple ways requiring coordination. The complexity of these systems is further increased by the relative low degree of standardization. Second, as I will show below, they are an emergent technology that has undergone significant changes in both technical and market dimensions. Thus, this technology offers an excellent opportunity to examine how technological frames adapt to changes in the technical and market domains. Within the possible frames, I looked at those relating to standardization for two reasons. First, standardization issues appeared to be particularly salient to participants, who often referred to them as central to the industry's future. Second, as shown in the literature review above, standardization is key in dealing with complexity. Technological frames referring to the standardizability of technologies are particularly significant for the progress of a novel technology as they influence the perceived scalability of the product.

Study design

I applied a triangulation approach consisting of in-depth semi-structured interviews, a documentation review, and observational data. This approach was used to ensure consistency, data trustworthiness, and internal validity of the study (Denzin, 1978; Woodside, 2010). The collection and review of documental data was the first step in the research process to gain a deep understanding of the microgrid market in general and its growth barriers in particular before proceeding to other information sources. The review also helped to identify key actors to be included in the purposeful sampling for the next step of data collection via semi-structured in-depth interviews. These two phases eventually overlapped. Interviews functioned as the main data source on microgrid market dynamics with archival data serving as supplementary sources to expand the covered time period, support existing and gain additional perspectives on central issues. Observations at field configuring events such as practitioner conferences served as an additional information source on key issues. Data collection, inductive analysis, and the selection of new informants using the snowballing technique were iterative and simultaneous processes. This resulted into increasingly focused data and ultimately led to 'theoretical saturation' (Glaser & Strauss, 1967) when further data collection and analysis stopped yielding further insights with respect to the research question.

Sampling

Purposive sampling has been identified as the most suited technique for this study. This non-probabilistic sampling strategy is based on the assumption that the investigator wants to discover, comprehend, and gain insight and thus needs to choose a sample according to its suitability (Chein, 1981). This allowed me for selecting information-rich cases from which a lot can be learned about the topic of interest (Patton, 2002; Merriam, 2009). The selection criteria for the purposive sampling were established through the review of archival data. First, I explicitly chose informants that would be considered experts in the field and thus would be able to inform me on my main research question concerning the barriers hindering microgrid market growth. Key informants were found in the best position to provide important insights on the specialised product market that microgrids represent. Once I identified and established access to key informants, I then used snowball sampling, asking my existing informants to recommend contacts suitable to address my core questions, to identify information-rich cases (Suri, 2011). During the sampling process I took steps to ensure that the sample accurately represented a broad spectrum of experts on the product market.

Semi-structured interviews

In 2018 I carried out 34 in-depth interviews with selected microgrid industry experts which were all recorded and subsequently transcribed. Interviews lasted on average 46 minutes. I employed semi-structured interviews as they allowed me more freedom, compared to structured interviews, in following up on the angles the interviewee regarded as important. Compared to unstructured interviews, the interviewer can better influence the focus of the conversation to address issues related to the research study (Brinkmann, 2013). Interviews were used to collect both retrospective and real-time accounts by industry experts on the evolution of the technology. Interview questions were adapted along with the progression of the study. Interviewees covered a wide spectrum of industry experts. Table A1 provides an overview of interviewees and interview durations.

Archival data and observations

The archival data consisted of proceedings from practitioner conferences, industry publications and magazines, microgrid news and company websites, white papers, case studies, and academic journal articles. Industry news websites such as microgridknowledge.com and utilitydive.com allowed me to keep track with industry developments on a weekly basis throughout the duration of this study. Regular updates were also accessed via specialist consulting and research firms such as Guidehouse (formerly Navigant) guidehouseinsights.com. I examined these sources regularly and subscribed to available newsletters. I also scheduled regular calls with one key informant to discuss the industry’s progress.

I used several opportunities to engage with experts directly and observe both the work of experts and the technology. Specialist conferences and events helped providing access to world-leading experts on microgrids. Two events have particularly contributed to this study: A two-week field study visit to California in 2018 enabled me to gain first-hand impressions of a leading working microgrid (Stone Edge Farm) and to experience the work of leading microgrid developers. California is a leading state when it comes to microgrid development. I had the opportunity to interview experts from two universities in San Diego: The University of California San Diego (UCSD) and the University of San Diego. The former is home to one of the most advanced campus microgrids, showing the State of California's and San Diego's leading role in the development and implementation of microgrid projects. A further example of the region's leading role in microgrid development is 'San Diego Gas & Electric's (SDG&E)' microgrid at Borrego Springs. During my visit I was based at a leading microgrid software developer which enabled me to engage in daily conversations with industry stakeholders. Notes were taken either while engaging in conversations and during visits or directly afterwards. After the trip ended, I kept in touch with one industry expert for frequent phone calls and email exchanges that lasted for the full duration of this study and beyond.

The second event was the International Microgrid Symposium in 2018. This invite-only yearly event has been taken place since 2005 and has the purpose of providing a platform for world-leading microgrid experts to exchange insights on the current state of microgrid research. Key events during my study are listed in Table 3.

Table 3: Conferences and Events

Conference/ Event Title	Location	Date
Westminster Energy, Environment & Transport Forum Keynote Seminar	London, UK	12.12.2017
Field study visit	California, USA	13.04.2018 – 28.04.2018
International Microgrid Symposium	Bucharest, Romania	02.09.2018 – 05.09.2018
Westminster Energy, Environment & Transport Forum Keynote Seminar	London, UK	09.06.2020

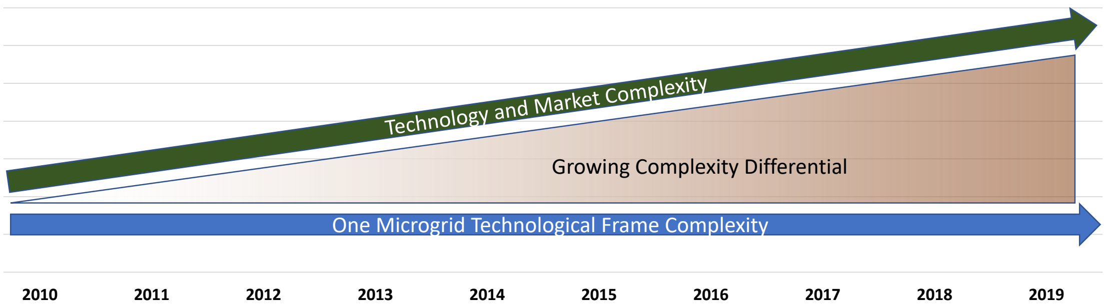
Data analysis

I applied an analytic induction strategy in order to systematically examine "similarities within and across cases to develop concepts, ideas, or theories" (Pascale, 2011: 53). The analysis was done simultaneously with data collection as suggested by Glaser and Strauss (1967). I followed Bogdan and Biklen (2007) as a guideline and inductively coded data while collecting it. This allowed me to identify patterns and formulate possible explanations of these patterns while also ensuring that the data is not unfocused or repetitive (Brinkmann, 2013; Merriam, 2009). This approach gave me the flexibility in data collection to account for the fact that I could not know what exactly will be discovered and which informants will contribute the most (Merriam, 2009). I used Corley and Gioia (2004) and Gioia et al. (2013) as a guideline for my data analysis. I first applied an open coding technique to identify initial concepts in the transcripts and grouped them into categories relying on 1st-order codes to not change the language used by informants. Next, I applied axial coding to seek relationships between these categories to establish 2nd order themes. Finally, I combined themes into overarching dimensions. This represented a recursive process that continued until the theoretical relationships became clear.

FINDINGS

My findings document the emergence and transformation of a collective technological frame. I begin by presenting a brief overview of the case. I then draw on my processual and thematic analysis to explain the factors leading to a misalignment of the technological frame and ultimately to key actors perceiving the necessity for an active frame transformation. I show how complexity differentials act as a mechanism for frame transformations. I find that applying the concept of complexity differentials to technological frames improves our understanding of frame dynamics. I follow the trajectories of the market and technology focusing on relative complexity levels captured by the complexity differential concept. I show how a technological frame with a stable level of complexity then became misaligned leading to a growing complexity differential. This was shown by some actors perceiving an excessive difference between the complexity of the frame and the complexity of the technology and market environment. The increasing perception of a complexity differential led to frame instability and ultimately to a frame transformation. This transformation produced a shift from the dominance of one cohesive frame to a group of broadly similar but fragmented frames that better matched the complexity of the technology and the market. Thus, I show that the increasing perception of a complexity differential between the frame's content, technology, and the product market leads to a frame transformation and shift in dominance of the technological frames (Figure 1).

Figure 1: Increasing Complexity Differential between Technological Frame and Technology & Market Complexity



Early developments: the age of the one microgrid frame

Microgrids vary in their degree of complexity. A very simple microgrid may be used to power a single household in a remote area using two forms of distributed energy generation, a simple microgrid controller, and is not connected to the main grid. On the other end of the spectrum is a highly complex microgrid that supplies multiple loads using a broad spectrum of distributed energy resources including renewable energy, uses an advanced control system and sophisticated energy storage system and can smoothly connect and disconnect from the main grid (Wood, 2016a). Complex microgrids are characterised by several distributed energy resources which may not have a common voltage, are connected according to a complex topology, and require advanced microgrid controllers to orchestrate and optimise the microgrid's components (Bidram & Davoudi, 2012; Cucuzzella et al., 2017; Han et al., 2016; Mahmoud, 2017).

Historically, microgrids used fossil-fuels to generate power for remote locations with limited access to electricity with the purpose of establishing or increasing power reliability (Vine & Morsch, 2017; SEPA & EPRI, 2016). More recently this was followed by an increase in integrating renewable energy resources focusing on solar energy and as a consequence of intermittent resources also the integration of energy storage technologies into microgrids (Vine & Morsch, 2017). The first adopters of such more advanced, complex microgrids were military bases, universities, and research facilities (Deloitte, 2016). However, as the industry developed, complex microgrids became increasingly widespread (AhmadiAhangar et al., 2019; Wang et al., 2014). Because the technology was still developing and there was limited standardization, as discussed above in the 'Setting' chapter, interworking protocols to create a 'plug and play' platform were missing [ref]. Thus, complex early microgrids were typically highly customized projects. "For years during the microgrid industry's infancy, the criticism has been that yes, microgrids provide valuable services, but they are too expensive. That has largely been because each one typically involves its own unique and bespoke 'science project' approach" (Kelly-Detwiler, 2019). Indeed, customization and integration efforts are extremely expensive and can contribute up to 60% of the total project costs (van den Berg et al., 2016). This translated in a concern with lack of standardization "I define three main barriers to microgrids: One is the non-standardization, second is the complexity of the system, and the third one is the rigidness of the design" (07, 2018). Table 4 provides further evidence for that these beliefs were widespread.

Table 4: Non-standardization as a Barrier to Microgrid Adoption

Non-standardization issues	Evidence	Source
Market-wide problem	"If you want to summarize the microgrid problems in on word, it's customization, right. Every single product is different, and you need to customize it."	07, 2018
	"The 'hyper-specific' nature of microgrid projects has held back their growth."	Walton, 2015
	"Where the gap is, is to have a really standardized approach that utilities are comfortable with in terms of the way they operate the distribution system because it's very important that a microgrid be considered part of that overall grid. Utilities, it has to be part of their planning process, the tools to integrate that technology with their operation so that they can see it and control it. It all has to be standard."	03, 2018

Table 4: Non-standardization as a Barrier to Microgrid Adoption (cont.)

Non-standardization issues	Evidence	Source
Held back microgrid technology adoption	"An obstacle to adoption is the fact that the technology is not standardized."	Runyon, 2017
High costs	"…customization…has one major downside—time and money costs."	Asmus, 2019
Reduced accessibility	"Developers were building microgrids in a one-off fashion: an approach that unfortunately made microgrids available to the few and not the many."	Wood, 2018
Interconnection difficulties	"Standardization can also help overcome regulatory obstacles, such as the complexity of interconnecting to utilities—often a big hurdle to both microgrid and solar developers."	Goodman, 2019
Investment risks	"Standardized designs can also decrease real or perceived risk on system performance for prospective investors."	Weston et al., 2018
	"At the end of the day, microgrid projects have to make business sense and have to have a solid business case. With the current approach to microgrids, when everything is re-engineered from the ground up for each project, it makes it difficult to see the value with confidence."	Stadler, In: Cohn, 2018

An issue that was particularly central to this view was that lack of standardization hindered market growth. Soam Goel, Partner at Anbaric Development Partners, a company specialising in large-scale electric transmission and storage solutions (Anbaric, 2020), stated in 2017 that microgrids require a combination of utility adoption and higher degrees of standardization to overcome market growth barriers (Nussey, 2017; Runyon, 2017). Ustun and colleagues noted in 2011 that "For microgrids to be embraced rapidly and implemented easily, there is a need for systematic standardization and universalization in all aspects of this field. This would not only help in bringing different organizations together but also encourage more people to accept transition to microgrid. If standard procedures are implemented and universalized components/ interfaces are utilized instead of re-inventing the wheel for every single microgrid project, past experiences can easily be put into practice" (Ustun et al., 2011: 4040). Four years later the non-standardization remained a perceived barrier for market development: "In a market where every (microgrid) project is very different, it makes it difficult to produce the standardized, cookie-cutter platform which is often sought-after" (Saadeh, 2015). Thus, the lack of standardization has been identified as a major barrier for microgrid adoption and market development for a long time and has been a continuous conversation topic within the microgrid community (e.g. Cohn, 2017; 2018; IEC, 2014; Klustner, 2015; Kroposki et al., 2007; 2008). At the same time, lack of standardization was largely perceived as inevitable. The reasons included factors such as the high variety of vendors, applications, distributed energy resources (DERs), customer requirements, and location-specific requirements. Table 5 provides evidence for each of these factors.

Table 5: Rationales for justifying Non-standardizability

Source of uniqueness	Evidence	Source
High variety of vendors for components	"If you literally want to make your house into a full fledge microgrid, you're going to have to deal with many different vendors and I don't think anyone's going to … that's not scalable."	09, 2018
	"I think the problem right now is (that) there's too much variability"	
High variety of microgrid applications	"Talk about standards for microgrids is to talk about a soviet plan city where every apartment block is exactly identical to each other."	21, 2018
High variety of possible DER combinations	"Every microgrid is unique because it integrates a range of distributed energy generation."	UL, 2016
High variety of customer requirements and needs	"When you've seen one microgrid, you've seen one microgrid. This saying exists for a reason: The one thing everyone does agree on is that there's not necessarily a 'standard microgrid', by definition, each project is designed and engineered to meet a specific customer's set of requirements."	Chenoweth, 2018
	"A common refrain was 'If you've seen one microgrid, you've seen one microgrid'. Attendees agreed that microgrid solutions are often bespoke and built to serve unique customer needs."	GI Energy, 2019
	"Microgrids are unique, with customer-specific customization occurring on many levels."	Dupont, 2019

Table 5: Rationales for justifying Non-standardizability (cont.)

Source of uniqueness	Evidence	Source
Location-specific differences in regulations and preferences	"We worked with a Microgrid setup in Norway, in Germany, and on Malta. And all countries differed in regard to the specifics of regulation, they differed in regard to customer preferences, and so on."	19, 2018
	"On the physical side, every site is absolutely different and there's no way to standardize microgrids from that perspective."	29, 2018
	"Over the last two years, everything that's been done has been kind of an engineering project. Everybody kind of hand-picked their components, had to design their architecture from scratch and then installed it. Then it takes two to three months to get everything working and talking together."	Colthorpe, 2018
	"You realize each microgrid … is installed in different locations for different customers that have very different engineering requirements and financial requirements."	08, 2018
	"Each one (microgrid) is entirely unique in its precise features and … structure because of the necessity of adapting to each location on an individual basis. What works in one place may not work in another so as Art says, 'If you've seen one microgrid, you've seen one microgrid'."	Martin, 2019
	"We cannot standardize because we have to do it (develop microgrid projects) case by case."	13, 2018

A technological frame describes the assumptions, expectations, and knowledge of actors to understand the microgrid technology. The quotes I have discussed above point to a technological frame that is built on knowledge gained through past experience in microgrid projects. Frame holders assume microgrids to be too technologically complex and too linked to individual customer requirements to be standardisable; and expects this state of affairs to be unchangeable as they construct complexity and customization as inherent characteristic of microgrids. This frame became encapsulated in the 'one microgrid' phrase: **"If you have seen one microgrid, you've seen one microgrid"**. The phrase was reportedly coined by David Chiesa, one prominent member - S&C Electric's former senior director for global business development, at an industry conference in 2013. The phrase gained industry-wide attention in the following years as it quickly spread through microgrid industry conferences with various interpretations and meanings assigned to it. The phrase achieved such a presence over the years that the S&C Electric Company included it as a myth in one of its education reports (S&C Electric, 2018). The technological frame this study focuses on has become an industry mantra by originating from a well-established actor and being widely shared at practitioner as well as academic conferences and through trade journals and articles leading to industry-wide recognition.

The phrase provided a definitive shape to the technological frame and thus facilitated its diffusion. For instance, Wood (2018a) devoted an entire article to the 'one microgrid' phrase in late 2018 stating that: "Some quotes become sticky. Such is the case with: If you've seen one microgrid, you've seen one microgrid". Further evidence provided in Table 6 shows how the 'one microgrid' phrase became a commonly used shorthand to refer to the dominant industry frame that had the non-standardizability of microgrids at its core.

Table 6: References to 'One Microgrid' Phrase

Quote	Source
"'When you've seen one microgrid, you've seen one microgrid' is a common refrain in the energy world for a reason."	Jutras, 2018
"Last, another respondent replied: "If you've seen one microgrid…you've seen one microgrid," to highlight the uniqueness of each microgrid project."	Giraldez et al., 2018
"First off, there's a saying that if you've seen one microgrid you've only seen one microgrid, 'cause they're all different."	31, 2018
"As the industry saying goes You've seen one microgrid—you've seen one microgrid"	Asmus, 2019

The 'one microgrid' technological frame gained prominence among stakeholders because it reflected and addressed a key characteristic of many microgrid projects, namely their high customization. Frame holders frequently referred to the non-standardizability of microgrid projects as a given characteristic while acknowledging that higher standardization would be beneficial to the market. The customization requirement as emphasised by the technological frame was accepted as a fact with no exceptions "…because they are all different" (31, 2018) despite the market's awareness of it being a major drawback. Actors frequently referenced the non-standardizability of the technology in form of the 'one microgrid' technological frame as a given fact not questioning its accuracy – it was a taken-for-granted 'truth' about the industry. Stakeholders perceived the technological frame to be accurately aligned with what they believed to be the un-addressable customization of the technology despite the general awareness that the lack of standardization had held back market growth.

The emergence of microgrids with higher levels of standardization and multiple business models

Despite the dominance of the 'one microgrid' frame, microgrids with a higher level of standardization compared to the highly customized microgrids described earlier increased throughout the observed period. "People have started to pre-package complete systems with inverters, batteries, switchgear and then you tie that in with the generator and you drop-ship pretty much a complete system to a site where you're then just making external connections rather than wiring the entire system onsite" (Colthorpe, 2018).

One way to classify microgrids according to their level of standardizability is to divide them into engineered systems, packaged systems, and productized systems (Hepp, 2019). Engineered systems, which were implemented first, represent highly customized microgrids with site-specific engineering and custom designs (Hepp, 2019). Packaged systems have some degree of standardization of components but still provide customers with some flexibility for customization and allow for site-specific optimisations. These systems have a simplified design and are easier to install and operate compared to engineered systems (Naik-Dhungel, 2017). Productized systems represent the most standardized microgrids. The highly standardized microgrid systems are pre-tested and offer only few options for customization (Hepp, 2019). Both packaged and productized systems have been available for several years. Early studies exploring the feasibility of packaged and productized microgrids date back to 2008, while the first commercially available systems were developed around the mid-2010s (John, 2016). Options to standardize microgrids in form of packaged or productized systems were therefore introduced several years ago and have consistently gained prominence while the 'one microgrid' technological frame remained dominant. Table 7 summarises key characteristics of these three systems across five dimensions: standardization of components, service, flexibility in integrating distributed energy resources (DERs), cost effectiveness, and design. This classification allows us to analyse the transformation in technological frames of microgrid stakeholders as reflecting a shift from narrow framing only considering engineered systems to a broader framing with higher complexity that also considers packaged and productized systems. For an overview of early studies and articles that introduced the concept and provides evidence for implemented microgrids with higher degrees of standardization in form of modular and containerized microgrids (packaged and productized systems) see Table 8. Increased standardization was key in attracting utilities "So as it happens, utilities will not put one offs all over their system, that's just not what they're gonna do" (33, 2018). The increased interest by utilities and other larger investors further contributed to the diffusion on more standardized microgrids.

Increasingly diverse business models

In parallel to the emergence and diffusion of more standardized microgrids, which made the product space more complex introducing the packaged and productized options, the market space also became more complex through the increase in the number of microgrid business models over the last decade. The single-user business model represents the base model with the lowest level of complexity (Bellido et al., 2018). Single-user and owner microgrids are financed, owned, and maintained by a single entity (Asmus & Lawrence, 2016). Under this model, the microgrid is only supplying loads to one consumer, such as a hospital or university campus, who will also be responsible to bear all the costs and risks (Castro, 2020). This business model therefore has a low level of complexity and, being the traditional format, is not innovative. With increasing complexity of microgrids through the integration of a higher number and variety of distributed energy resources, advanced energy storage systems, and loads, the simple single-user business model becomes less suitable restricting their growth potential, since the high complexity prevents most single entities with limited capabilities to implement and operate advanced microgrids (Bellido et al., 2018). The increase in complexity thus often leads to a shift to private developers and the application of energy-as-a-service (EaaS) business models (Asmus & Lawrence, 2016). More advanced and complex business models such as the multi-user and EaaS business models become more relevant with increasing complexity of microgrid systems along with technological progress, falling cost of DERs, and reduced regulatory barriers which also increasingly attracts utility firms (Bellido et al., 2018). The introduction of more complex business models has contributed to the overall market complexity (see Table A2).

The one-microgrid frame becomes increasingly inadequate

The 'one microgrid' technological frame [TF1] possessed a low level of complexity as its content and structure were simple, as it did not contain multiple interacting elements – it simply stated the uniqueness of each microgrid. The 'one-microgrid' framing thus only accommodated custom microgrids with site-specific engineering. As many interviewees stated: "All systems are different" (e.g. 07; 08; 29; 31). As a consequence of this narrow framing, other types of microgrids with higher degrees of standardization, that emerged throughout the covered period, such as pre-engineered packaged systems and productized systems were excluded leading to an increase in complexity differentials. The 'one microgrid' technological frame filtered valuable information as it did not reflect those types of microgrid products that were standardizable and available in the market. While the technological frame accurately reflected the microgrid market at an early stage, it increasingly failed to recognise innovation in form of more standardized microgrids.

Table 7: Types of Microgrid Systems

	Engineered Systems	**Packaged Systems**	**Productized Systems**
Standardization of components	Low Project-specific customization	Moderate/High Pre-engineering of subsystems Standardized components and controller	High Factory built Standardized components and controller
Service	Custom	Standard Packages	Standard Packages
Flexibility	High Custom integration of DERs	Moderate Flexibility to use many DERs Some flexibility in subsystem components but site-specific control and automation schemes	Low Pre-selected DERs and product options
Cost effectiveness	Low	Moderate/High	High
Design	Custom design High site-specific engineering	Engineered-to-Order	Configured-to-Order

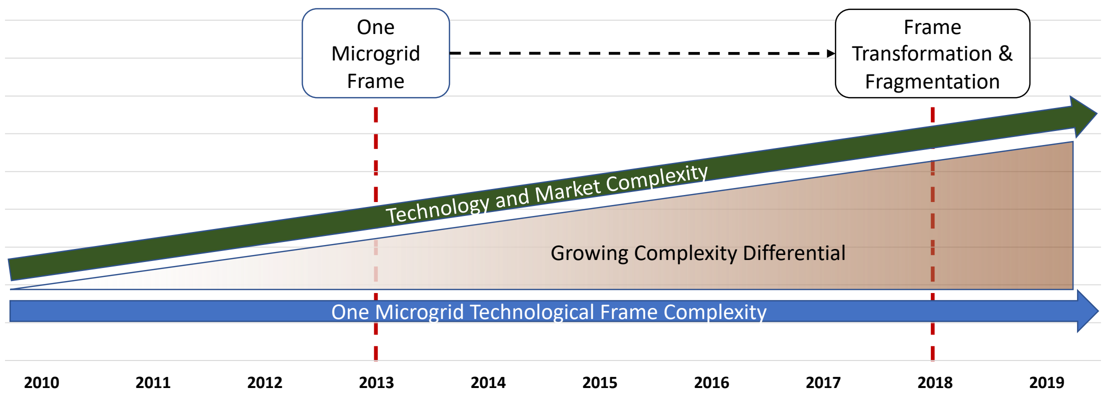
Adapted from: Hepp (2019). Microgrid Solutions: IDEA Campus Energy 2019

Table 8: Early Studies of Modular and Containerized Microgrids

Type of Study/Article	Title	Reference/ Year
Modular	Design considerations for rural modular microgrids	Cronje et al., 2012
	Modular power architectures for microgrid clusters	Lin et al., 2014
	A novel design for an expandable, modular microgrid unit	Falahati et al., 2016
	An Update from the World's First Modular Microgrid	John, 2016
Containerized	Promotion of microgrids and renewable energy sources for electrification in developing countries	Alzola et al., 2008
	Polygeneration energy container: Designing and testing energy services for remote developing communities	Paleta et al., 2014
	A novel flow invariants-based approach to microgrid management	Gamage et al., 2014

It should be noted that technological frames should facilitate decision-making by reducing uncertainty and complexity through simplification. A complexity differential between a technological frame and underlying technology is necessary as frames have the purpose to reduce the perceived complexity of the technology and product market they describe. This, however, should not be achieved by excluding key information necessary to accurately judge the technology and its adoptability. The advancements and innovation of the market and technology increased the number of elements that were not captured by the frame which led to an increased misalignment. The 'one microgrid' technological frame oversimplified both the technology and market it described. The changes described above, made key actors within the microgrid market increasingly uncomfortable with the 'one microgrid' technological frame. Stakeholders became gradually aware that demands of many customers can be met with fairly standard products. The issue I am describing in the following therefore does not relate to the complexity differential per se but to its growth over the observed period due to an increase in the technology's and market's complexity. The static complexity of the 'one microgrid' technological frame in combination with increases in complexity of the underlying technology and market led to a growing complexity differential. The growth in the complexity differential is illustrated in Figure 2. The complexity differential reflects the growing misalignment between the technological frame and the technology and market it describes.

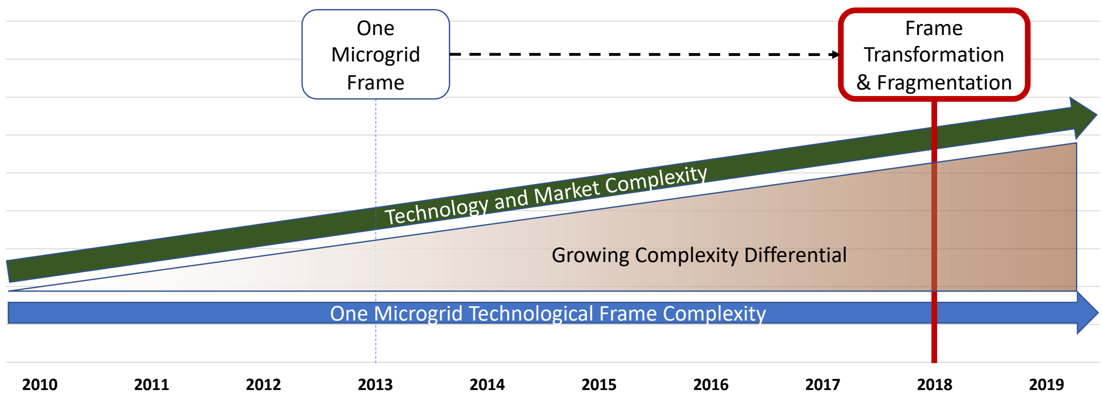
Figure 2: Growing Complexity Differential



The ascendency of the pro-standardization frame

The tensions between the 'one microgrid' technological frame dominating the industry and the evolution of microgrids came to a head in 2018, when after around five years in existence and increasing challenges, key actors moved to achieve a frame transformation (Figure 3). The frame transformation emerged as a consequence from the described technology and market dynamics leading to a growing dissatisfaction of key stakeholders with the 'one microgrid' frame.

Figure 3: Growing Complexity Differential leading to Frame Transformation in 2018



The following quote represents the re-framing activities initiated by Chiesa to transform his phrase that developed into the 'one microgrid' technological frame: "I'm trying to kill that phrase now because we're at the point in time where we should no longer be focusing on this uniqueness of microgrids. We need to make them more production-oriented where we get some standardization into the marketplace." [Chiesa, D., 2018].

Table 9 provides evidence for reframing efforts of actors who want to transform the framing from focusing on technology uniqueness towards a higher degree of standardization.

Table 9: Frame Transformation

Drivers	Evidence	Source
Simplification through standardization	"We need to work on simplification to get the adoption curve moving faster."	Chiesa, 2018, In: Wood, 2018a
Re-focusing on implementation	"We're at the point in time where we should no longer be focusing on this uniqueness of microgrids. We need to make them more production-oriented where we get some standardization into the marketplace."	33, 2018
	"There was one gentleman who is sort of a leader in microgrids around here, from S&C Electric, who used to use the phrase, 'if you've seen one microgrid you've seen one microgrid'. So at this year's conference in May in Chicago, he got up on stage and he said, 'I want to basically kill that phrase. It no longer applies.'"	27, 2018

Table 9: Frame Transformation (cont.)

Drivers	Evidence	Source
Re-focusing on implementation	"Our main market is utilities and we're talking about rolling this out in a large deployment. So as it happens, utilities will not put one offs all over their system, that's just not what they're gonna do. So you look at it, it's a safety issue for the utilities, it's a management issue for the utilities so that they don't have to have stocks and shares and everything else, and it's a cost issue for the supplier, which is us, in that we need to be competitive with all the other companies that are coming into the area. So, standardization really covers all of those problems. It covers all the customer problems, it covers all the supplier problems, and makes them all better."	33, 2018
	"At the end of the day, microgrid projects have to make business sense and have to have a solid business case. With the current approach to microgrids, when everything is re-engineered from the ground up for each project, it makes it difficult to see the value with confidence."	Stadler, In: Cohn, 2018
Re-focusing on replicability	"Almost every microgrid was unique. So the industry lacked replicability, stifling its ability to grow, drive down costs and achieve scale. Now, however, it is time to retire the ['one-microgrid'] phrase."	Wood, 2018a

The reframing activities of the 'one microgrid' technological frame have the purpose to shift the view of microgrid stakeholders being pessimistic towards standardization to consider a broader more complex perspective that seeks to make microgrids more production oriented and bankable. The frame was not rendered obsolete by market dynamics alone. It required the support of active re-framing activities to at least partially correct the misalignment with the market in particular with customer expectations. The re-framing activities aligned the complexity of the 'one-microgrid' technological frame more with the complexity of the technology and market.

The following quote illustrates the view of the group of actors that have distanced themselves from the 'one microgrid' frame by applying a higher resolution to the product market: "I'm not saying that there aren't custom microgrids going on, because a big complex site is gonna want any kind of energy project to be customized.

But these are the smaller commercial and industrial facilities that don't need that kind of customization and are just fine with a small modular container microgrid" (27, 2018). While this technological frame has been present for a while, it was only supported by a minority in the early development stages of the technology market. We name this frame the pro-standardization frame. Holders of the pro-standardization (TF2) group of technological frames were confident that the necessary standardization is both important and achievable. Table 10 provides further evidence for the pro-standardization frame holders' problem-solving approach towards standardization.

Table 10: Representative Evidence for the Pro-Standardization Frame

	Evidence	Reference
Problem-solving approach towards standardization	"Because microgrid projects are complicated, the industry needs to find ways to standardize them."	Goodman, 2019
	"The end goal should be configurable standardization, stripping out costs linked to inefficiency while delivering greater customer value through creative plug-and-play platforms. Though few microgrids are identical, the industry can build upon the tremendous technological progress with devices such as smart inverters, ES, and software that has occurred over the past 5 years"	Cherian & Asmus, 2016
	"Well, if you have unique devices all over your system, if you've seen one microgrid, you've seen one microgrid, then the lineman doesn't know how to approach that, and these are still high-voltage systems." They can get people hurt. So, as a result, you have to at some point get towards standardization really as a safety issue"	33, 2018
	"If you nail one (microgrid) comprehensively, mathematically, financially, then minor variations will work for all such microgrids worldwide and that kind of standardization is necessary and not too difficult in my opinion."	34, 2018
Emphasising advantages of standardization	microgrid systems with higher degrees of standardization are "…cheaper, smaller, they're easier to install, they're more universal."	27, 2018

Complexity of the Pro-Standardization Frame

The pro-standardization frame had a more complex structure compared to the ‘one microgrid’ frame. The complexity is reflected by the higher number of elements that enabled frame holders to consider a broader spectrum of technology systems. As one interviewee told us “There are a dozen aspects, not just technologies, but a dozen aspects of microgrids that would benefit from standardization and potential certification” (08, 2018). Table 11 provides an overview of key metrics comparing TF1 with TF2 and Table 12 shows the broader spectrum of frame elements in comparison to the one element (all microgrids are the same in their uniqueness) of the ‘one microgrid’ technological frame.

Table 11: Key Content of Technological Frames and their Complexities

	Technological Frame 1 [‘one microgrid’ frame]	**Technological Frame 2** [‘pro-standardization’ frame]
Key content	Each microgrid is unique	Standardization is possible and required to reduce complexity. More than one type of microgrid with varying degrees of standardization
Complexity [number of Frame Elements]	Lower	Higher
Rationale for Complexity Level	Narrow Framing	Broader Framing
	Non-consideration of various methods to increase standardization	Consideration of methods to standardize
	Discouraging problem-solving	Encouraging problem-solving
Differentiation	No differentiation	Differentiated perspective

Frame granularization

The newly dominant frame, as a consequence from its complex structure, was not as unified and cohesive as the ‘one-microgrid’ frame. Thus, rather than a single frame, we can see a granularization of technological frames. Vaccaro et al., (2011) introduced the concept of ‘granularization’ to frames to describe the decomposition of a frame into sub-components. This facilitates innovation as frame holders can focus on specific sub-problems while being aware of the broader issue (Cornelissen & Werner, 2014). I refer to the overarching frame that includes sub-frames that have their holders' positive attitude towards product standardizability in common as the pro standardization frame. The granularization allows frame holders to address the problem of non-standardization from different perspectives by focusing on a variety of key aspects related to the microgrid technology that require standardization. The granularization can be explained by the higher complexity of the pro-standardization technological frames. They incorporated more frame elements and were thus able to show a broader variety of the available technology options in comparison to the simpler 'one-microgrid' frame. Actors within this group thus agreed on standardizability but differed in their opinion of what should be standardized. Table 12 provides evidence for the granularization of the pro-standardization technological frames (TF2).

Table 12: Representative Evidence for Variations in Pro-Standardization Frames

Type of granularization	Quote	Source
Engineering/ Design	"A containerized microgrid with a limitation in size based on solar plus storage is a solution to standardize on the engineering side."	30
Financing	"To standardize the financing approach, the energy as a service business model is a solution."	30
Regulations	"What needs to be standardized is the regulatory framework but not the microgrid itself."	17
Modelling	"We have to standardize how we model different technologies because then we could compare the different approaches and maybe assess how accurate they are?"	02
Purchase/ Installation	"The client has to go to three different people, everyone is telling different things. At the end of the day, you don't know what to do, then just give up. It should be a standardized approach like how you purchase a car, for example."	02
Communication	"The communication of the microgrid with the central grid needs standardization through regulation but not beyond."	17
Interoperability	"Standardization should mainly centre around the interoperability of systems."	35

TF2 enabled its holders to perceive the technology from more than one perspective, allowing for a variety of interpretations with regard to the standardizability of the technology. This may contribute to both the understanding of the technology and to a problem-solving approach that facilitates innovation. The pro-standardization frame

(TF2) with its more complex structure and content encouraged decision-makers to scan their environment more broadly and use a wider variety of information sources.

Summary of findings

First, I described the non-standardization issue in the product market that led to the emergence of the dominant 'one microgrid' technological frame. I then showed the increase in technology and market complexity and introduced the concept of complexity differentials as a concept to analyse the growing misalignment between the simple structure of the frame and rising complexity of the market. Second, I showed that growing complexity differentials between the product market and the technological frame destabilised the frame as it was not able to capture the opportunities the market offered. Third, I found that active intervention by key actors in form of re-framing activities became necessary as the dominant technological frame deviated too much in its complexity from the technology and market it described. The pressure for frame transformation stems from the increasingly negative consequences from belief systems that are preserving existing problems as opposed to encouraging problem-solving activities. The re-framing activities led to a frame transformation that shifted the dominance from the 'one microgrid' frame to a group of frames that better captured the rising variety of products in the market. The higher complexity of this group of frames also led to a more fragmented field of frames in comparison to the unified 'one microgrid' frame.

DISCUSSION AND CONCLUSIONS

Management studies have been criticised for not sufficiently acknowledging the role and importance of technology considering its growing influence for organisations (Orlikowski & Scott, 2008; Zammuto et al., 2007). One of several possible explanations for this paradox is the growing complexity of technological systems over the last decades (Zammuto et al., 2007), which increasingly contributes to the creation of black boxes that pose challenges to scholars not trained in technologies (Orlikowski & Scott, 2008). To address this, I adopted a technological frames perspective that allowed me to establish a focus on technology innovation. My findings suggest that complexity is an important construct in the study of technological frames. The main outcome and contribution of this work is the introduction of complexity differentials to the study of technological frames.

Figure 4 summarises my findings related to the difference in technological frame resolution between the 'one microgrid' and pro-standardization technological frames. The two dimensions, system flexibility (vertical axis) and standardization (horizontal axis), are based on Table 7 and refer to the flexibility of microgrid systems to integrate a wide spectrum of components (DERs) and the standardization of the microgrid systems. The frame resolution of the 'one-microgrid' frame is coarse and thus only captures engineered systems that are highly flexible to integrate components but lack standardization. The pro-standardization frame, on the other hand, possesses a finer resolution that enables its holders to capture the broader spectrum of available microgrid systems, adding packaged and productized systems to the frame.

Figure 4: Microgrid Systems and Frame Resolution

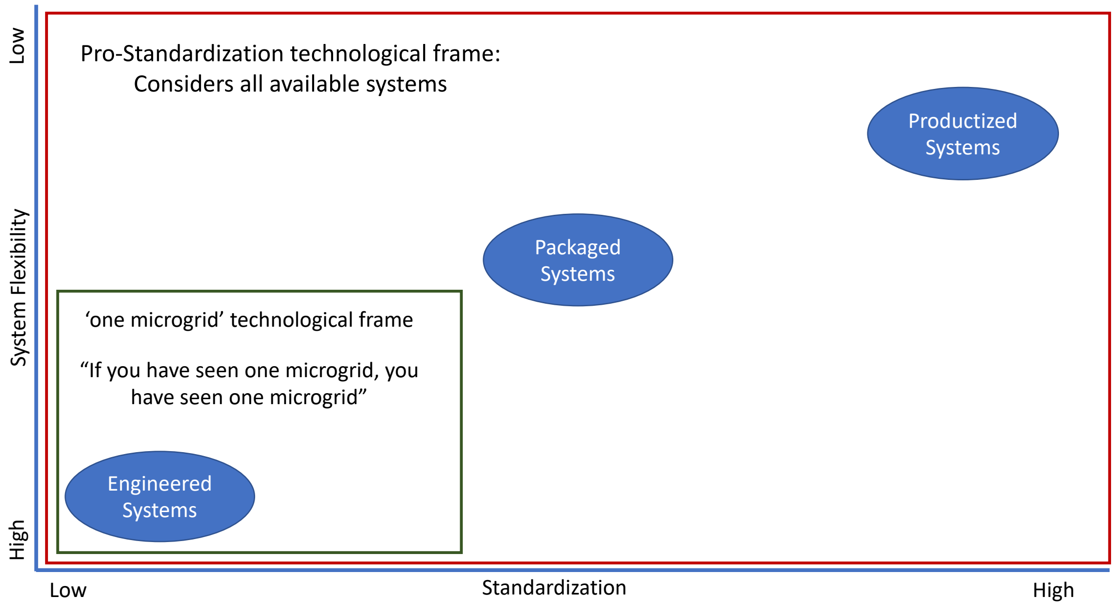
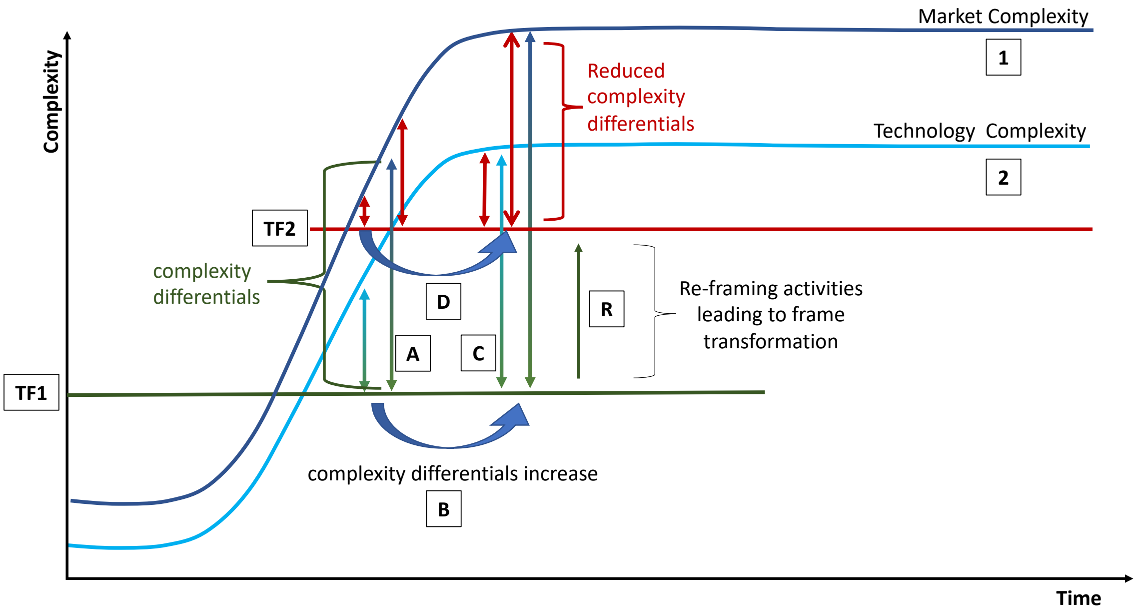


Figure 5 summarises the processes and dynamics described above along a time dimension (horizontal axis) and market, technology, and frame complexity (vertical axis). I follow Luhmann (1995:25-26) in arguing that the environment is always more complex than the systems or technologies themselves. Based on this, microgrid market complexity [1] is illustrated as being higher compared to technology (microgrid) complexity [2]. Both market and technology complexity increased leading to growing complexity differentials for both TF1 and TF2. TF2's complexity differential was, however, reduced compared to TF1 as it possessed a higher frame complexity. The reduced differential provided the frame with a higher stability as it more accurately reflected its environment.

Figure 5: Market, Technology, and Frame Complexity



The reduced complexity differentials between TF2 and both the market and technology complexity are illustrated by the red arrows in Figure 3. I found an increase in the complexity differential between the technological frame, the technology, and market over time. Both market and technology complexity increased for reasons outlined earlier with the technological frame keeping its low complexity structure. Once the complexity differential [A] increased [B] and got too large [C], re-framing activities [R] were required leading to a frame transformation. This led to TF1 losing ground and TF2, which more accurately reflected the complexity of the system and market, gained the upper end. As stated earlier, a key feature of frames is to reduce complexity to enable decision-making under uncertainty. Here it is argued, however, that the complexity differential cannot be too large because actors then perceived the frame as not useful. Once it has become too large the frame does not provide sufficient guidance and some actors engage in reframing activities. TF2 entailed a technological framing process that addressed the limitations of TF1. I find that frames that deviate significantly in complexity from the product or technology they refer to, are either oversimplified and thus might miss important information of the technology or they are overly complex which defeats their purpose of reducing complexity.

My analysis suggests that when a technological frame's complexity deviates too much from the technology it refers to, then the complexity of such a frame needs to increase in order to reduce overall complexity. In line with the concept of 'requisite variety', which states that a system that increases its complexity has a broader range of actions to cope with environmental complexity (Ashby, 1957; Luhmann, 1995; Schneider et al., 2016), technological frames also need to appropriately represent the system and market complexity in order to address it. This can only be achieved if the frame itself possesses a sufficient degree of complexity. Applying the concept of requisite variety, it is proposed that perceived market and technology complexity may be reduced by increasing the complexity of technological frames. Allowing for more frame elements, in our specific case by acknowledging a higher degree of standardizability through a broader variety of systems, increases the complexity of the frame itself but decreases the perceived complexity of the system. Re-framing activities can be applied to achieve a frame transformation and shift that increases frame complexity. This may lead to a more accurate interpretation of standardization options and opportunities. Based on my findings, I suggest the following propositions:

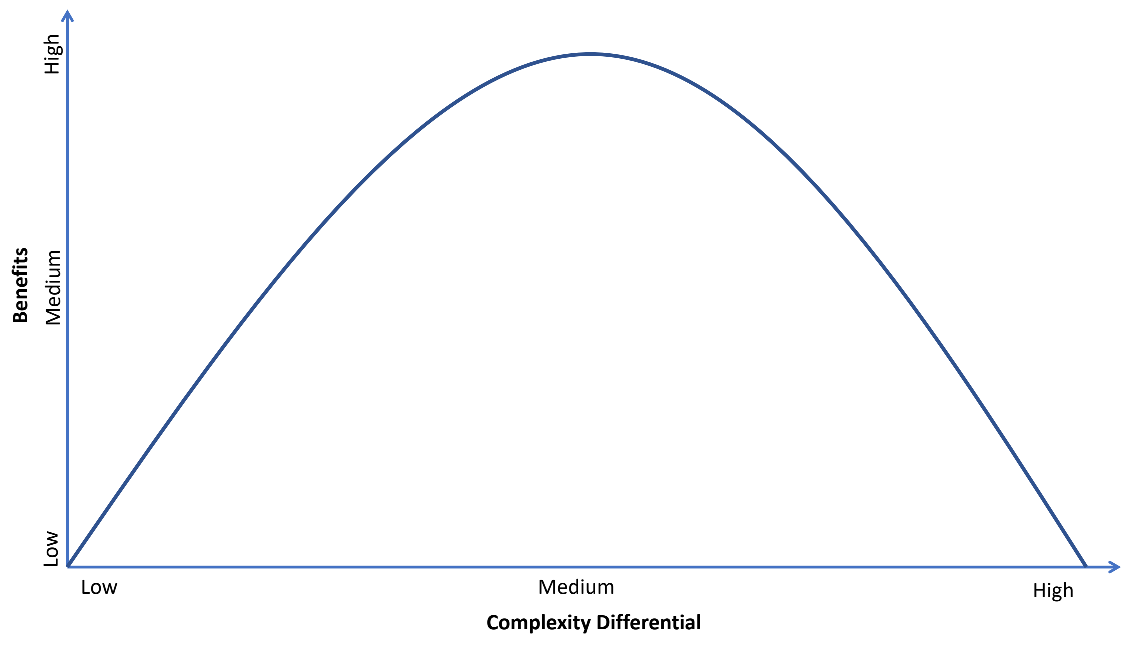
Proposition 1: Technological frames that restrict valuable information are threats to market development

I argue that the non-standardization ('one microgrid') framing observed in my study has similar effects than what the literature refers to as 'threat framing' (e.g. Gilbert, 2006) and the pro-standardization frame has similar effects than 'opportunity framing' (e.g. Dutton, 1992). Threat framing has been found to restrict information, to focus on controlling existing resources instead of searching for novel solutions (Dutton & Jackson, 1987), and reduce both the number of alternatives that are being considered (Shaw et al., 1981) and the number of decision-makers (Hermann, 1963). Opportunity framing, in contrast to threat framing, opens search processes, relaxes the inflexibility produced by threat (Dutton, 1992), and creates new sources of entrepreneurial growth (Stevenson & Jarillo, 1990). However, opportunity framing has been found to create less commitment than threat framing, resulting in a cognitive paradox. Flexible plans are created by opportunity framing which fails to inspire organisational commitment with threat framing creating the necessary commitment but failing to produce flexible plans (Gilbert, 2006). My study shows that technological frames that restrict information are more likely to be transformed and/or replaced.

Proposition 2: Curvilinear relationship between frame complexity differentials and benefits

I propose a curvilinear relationship between technological frame complexity differentials and benefits [see Figure 6 for an illustration]. Future studies could test this proposition empirically that neither a too low nor too high frame complexity achieves the same level of benefits as moderate complexity levels. I find that frames that deviate significantly in complexity from the product or technology they refer to, are either oversimplified and thus might miss important information of the technology or they are overcomplicated which defeats their purpose of reducing complexity. I therefore argue for a curvilinear relationship between frame complexity and benefits [see Figure 6 for an illustration]. The complexity differential can be illustrated also in terms of resolution. If the frame's resolution is too coarse to appropriately reflect the technology, then it will need to be adjusted or reframed to obtain a finer resolution that provides a better fit.

Figure 6: Curvilinear Relationship between Frame Complexity and Benefits



Conclusions

I find that an increasing complexity differential destabilises existing technological frames and ultimately leads to their transformation or replacement. This research explored the emergence and transformation of technological frames and what role complexity plays in those processes. Actors had conflicting technological frames about the standardizability of a technology system and about the direction the industry is taking. Key actors engaged in framing and reframing practices to shape the view on standardization within the market. I propose to apply the notion of complexity differentials to technological frames to offer a novel perspective on frame stability. In this paper I set out to explore the factors leading to changes in cognitive schemata of interpretation in form of technological frames. I applied a complexity differential perspective to technological frames to explain why frames may become unstable over time leading to their transformation and/or replacement. My study provides a novel perspective to conceptualise the dynamics leading to technological frame transformation and/or replacement.

Finally, my findings have some useful implications for practicing managers. There is a potential for managers to influence the progress of their technology and market by identifying collective frames with high complexity differentials and engage in re-framing or frame transformation activities to abandon such problematic frames. This study also has some limitations. My focus on a single industry is a limitation but a multi-industry study would not have allowed me to achieve the same in-depth knowledge on framing dynamics. Also, I understand that complexity is a highly abstract concept that poses challenges with regard to operationalization and thus replicability.

It seems fair to say that my findings related to complexity differentials between technological frames and the technology/market based on my expert informants are also likely to be applicable beyond this particular market setting. Technologies often possess high levels of complexity and require framing to be understood by stakeholders. The relevance of the complexity the framing itself entails on the stability of technological frames seems a transferable finding to other product markets. My findings thus provide future studies on technological frames with an additional perspective that should be considered when examining market dynamics.

APPENDIX

Figure A1: Increasing Complexity of the Energy Industry

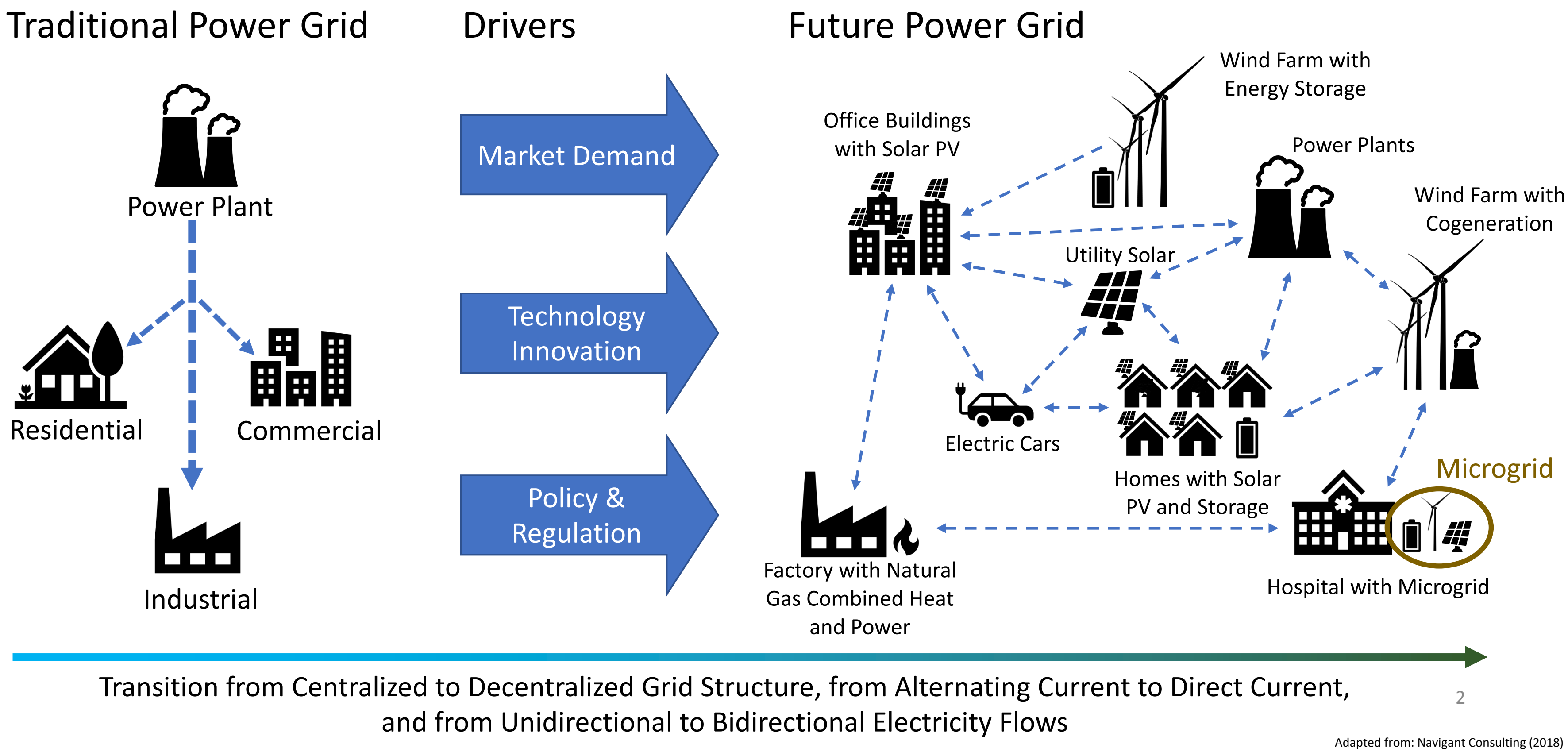


Figure A2: Increasing market complexity with shift from single to multi-entity ownership and operation

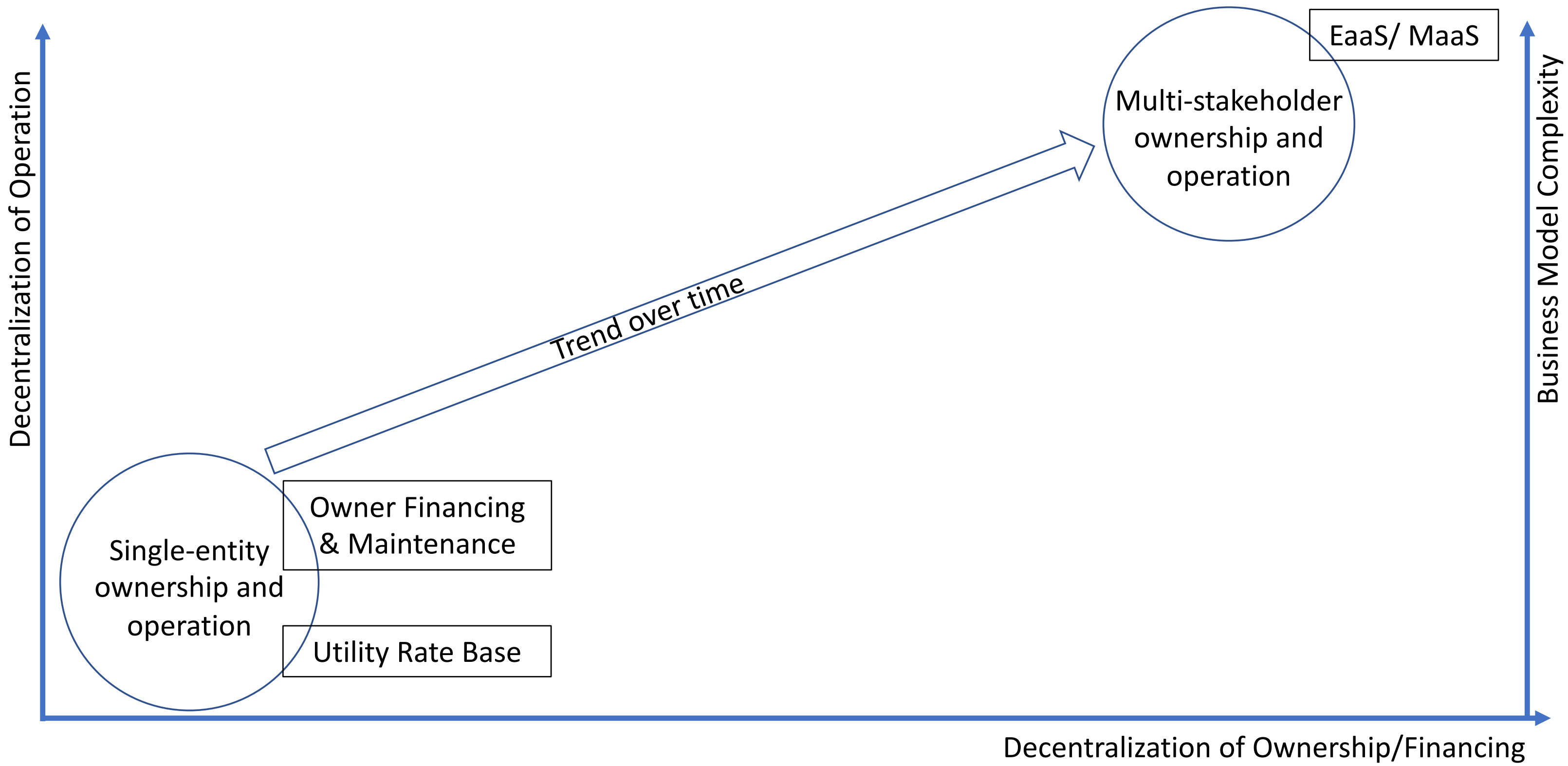


Table A1: Overview of Interviewees with Background and Position held

Interview Ident. #	Background	Position(s)	Interview Duration
1	Entrepreneur/Founder/MBA	Co-Founder/CEO	
2	Entrepreneur/ Academic/ Mechanical/ Electrical Engineer	Chief Technology Officer	00:34:00
3	Electrical Engineering	Vice President Grid Technologies	00:43:38
4	Entrepreneur/MBA	Managing Partner	00:29:04
5	Entrepreneur/Founder/Consultant	Consulting Project Manager	00:49:56
6	Researcher/ Civil Engineer	Principal Scientific Engineering Associate	00:49:38
7	Engineer/Entrepreneur	Lead Engineer & Co-founder	00:48:14
8	Academic/ Mechanical Engineering	Assistant Professor, Head of Research, Director of Energy Research Laboratory	00:27:00
9	Academic/ Mechanical/Industrial/Systems Engineering	Assistant Professor	00:58:56
10	Energy Company	Technical Director, Smart Power & Power Economics	01:00:57
11	Entrepreneur/Engineer	Partner / Principle	01:03:58
12	Entrepreneur/Engineer	Co-founder and COO	00:45:01
13	Academic/Electronic Engineering/ Microgrids	Professor, Microgrids specialisation	00:56:00
16	Mechanical Engineer/Advisor	Microgrid Advisor, Director of Energy Engineering	00:46:03
17	DER Company	Managing Director	00:39:00

Table A1: Overview of Interviewees with Background and Position held (cont.)

Interview Ident. #	Background	Position	Interview Duration
18	Consultant/ Electrical Engineer	Senior Consultant	00:31:33
19	Academic	Assistant Professor of Energy and Sustainability Management	00:48:20
20	Entrepreneur/ Founder/ Consultant	Co-Founder and CEO, Advisor at the U.S. Department of Energy	00:57:34
21	Consultant/ Mechanical Engineer	Director / Associate Director - Energy / Smart Grid	00:57:46
22	Consultant/ Civil and Environmental Engineer	Managing Consultant, Strategic Planning and DERs	00:43:13
23	Consultant/ Artist	Director	00:58:16
25	Consultant/ Environmental/Chemical Engineer	Associate Director	00:47:35
27	Editor/ Writer	Editor/Writer	00:52:13
28	Energy Management/ Economics	Director of Energy Services	00:48:07
29	Consultant/ Mechanical Engineer/ Strategy	Senior Research Analyst - Distributed Energy Strategy	00:55:21
30	Consultant/ Journalist	Research Director: Microgrids	00:44:01
31	Engineer/ MBA/ Mechanical Engineer	Microgrid Sales and Business Development Manager	00:35:12
32	Academic / Environmental Engineer	Microgrid Researcher	01:09:06
33	Sales, Strategy, Economics	Senior Director - Global Business Development, Microgrids, Renewables	00:40:54

Table A1: Overview of Interviewees with Background and Position held (cont.)

Interview Ident. #	Background	Position	Interview Duration
34	Academic/ Chemical Engineer	Founder and Visiting Professor	00:54:53
35	Material/ Nuclear Engineer/ Microgrid Developer	Vice President	00:38:00
36	Nuclear physicist/ Academic	Visiting Fellow; Founding Member	00:37:41
	Revisited		
8	Academic/ Mechanical/Industrial/Systems Engineering	Assistant Professor, Industrial and Systems Engineering	00:17:15
32	Academic / Environmental Engineer	Microgrid Researcher	00:47:14

Table A2: Representative Evidence for Increasing Market Complexity through Business Model Diversification

Quote	Reference
"Micrograds have come to embody resiliency. However, in recently deployed and prospective projects, a mixed-ownership model is aligning microgrids with broader energy goals." "The microgrid has traditionally been a skeleton concept with no one-size fits-all solution. A rise in multi stakeholder ownership models illustrates that different institutions and communities can find their own value proposition, building on the microgrid together to create an attractive and mutually beneficial business case."	Chen, 2016a
"A shift away from single-entity owned and operated projects is greatly improving microgrid project economics in the U.S. microgrid market." "A key driver of recent growth for the U.S. microgrid market, multi-stakeholder ownership models, arose from a surge in regulated utility interest to co-develop microgrids as a 'non-wires' alternative to capital infrastructure investments". "While microgrids have historically focused on behind-the-meter benefits for end customers, recent ownership trends suggest a very different future."	Chen, 2016b
"While customer-owned microgrids are standard, the new business model, Microgrids-as-a-Service (MaaS), offers a flexible ownership structure and an opportunity to capitalize on the growing market."	Engerati, 2014
"Customer-owned microgrids vs MaaS- Based on an industrial base case, with 10 MW of generation from solar and natural gas, as well as energy storage, the returns for the customer-owned microgrid and MaaS are exactly the same. However, with the customer-owned model, the customer has to carry all the financial risk".	
"Until recently, a large portion of microgrids has been third-party installations serving a single customer. However, utility-owned microgrids are also being developed, primarily due to state-level policies and directives. In tandem, technology maturity and expanding microgrid applications are also facilitating their development."	SEPA & EPRI, 2016
"…the hybrid 'unbundled' model (is now emerging) based on public-private partnerships, which could offer more flexibility and opportunities for collaboration."	Engerati, 2017
According to Navigant Research, "while in its early stages, the EaaS market consists of third-party vendors, utility services companies, and potential business model disruptors deploying niche technical, financing, or procurement solutions like solar [photovoltaic] power purchase agreements, energy services performance contracts, and deregulated electricity market retail brokerage services." "As the EaaS market matures, it could spur outsourcing of energy portfolios and turnkey vendors equipped with a comprehensive set of technical, financing, and deployment model options."	Proctor, 2018

Table A3: Representative Evidence for the Increasing Complexity in the Energy Industry

Description	Quote	Reference
Systems	"Energy systems become more and more complex"	Pina et al., 2018: 1
Increasing Decentralization	"Conventionally, power plants have been large, centralized units. A new trend is developing toward distributed energy generation, which means that energy conversion units are situated close to energy consumers, and large units are substituted by smaller ones."	Alanne & Saari, 2006: 539
	"Deployment of Distributed Energy Resources (DER) is already a reality for electricity supply and the debate whether distributed generation is going to replace almost totally or partially the current centralized generation paradigm is currently in place."	Martín-Martínez et al., 2017: 850
	"The global electric power industry is facing a transformation from centralized generation toward a more decentralized grid with two-way energy flows. New global DER capacity deployments—including distributed generation, DER, plug-in electric vehicle (PEV) charging load, demand response, and energy efficiency—are outpacing the deployment of new centralized generation capacity."	Danigelis, 2019
	"Electric power systems are riding the wave of decentralization through the deployment and use of 'distributed power' technologies. Originally established when Thomas Edison built the first power plant in 1882, distributed power technologies are used more and more today to provide electrical and mechanical power at or near the point of use."	Owens, 2014: 10
	"A big push to decentralization in the field of renewable energy has been given, in the last two decades, by public incentives, almost worldwide."	Di Silvestre et al., 2018: 486

Table A3: Representative Evidence for the Increasing Complexity in the Energy Industry (cont.)

Description	Quote	Reference
Integration challenge	"The large-scale deployment of distributed energy resources presents many unique challenges in terms of grid integration."	Kroposki & Mather, 2015: 18
	"Solar energy …is characterized by variability, intermittency, unpredictability, and location dependency and thus required energy storage systems for backup."	Naderipour et al., 2017
Rise in Complexity	"With increasing complexity and interconnectivity of the electric power grid, the scope and complexity of grid operations continues to grow."	Greitzer et al., 2008: 1
	"From centralized to decentralized power production; where both generation configurations mix together making it somehow complex."	Petinrin & Shaaban, 2012: 896
	"The addition of significant levels of renewable generators, such as PVs or WTs, may increase the complexity of these analyses due to the uncertain nature of the energy sources. For example, the time and location dependency of wind generators require extra care when combined with feeder location and load variability."	Naderipour et al., 2017
	"The recent changes in the area of power systems have significant effects on the complexity of the distribution and transmission system operation imposing new requirements. Prominent among these changes are: • Increase of penetration of Renewable Energy Sources (RES). • Increase of distributed generation and storage. • Market driven operation with prospective participation of small generation and simple consumer. • Demand for increased Power Quality with special focus on uninterruptible power supply and network self-healing capabilities."	Dimeas & Hatziargyriou, 2007
	"The introduction of microgrids in the power system introduces considerable complexity in the operation of the grid, but at the same time, it can provide distinct benefits to the overall system performance, if managed and coordinated efficiently."	Dimeas & Hatziargyriou, 2007

Table A4: Representative Evidence for Increasing Microgrid Complexity

	Quote	Reference
Complex Systems	"Microgrids contain all the elements of complex energy systems."	Shah, 2020
	"As MGs are complex installations, different actors are required in the planning, implementation and operational stages."	Warneryd et al., 2020
	"A community MG is a complex technical system."	Warneryd et al., 2020
Rising complexity	"The increasing complexity of microgrids caused an ongoing demand for more detail studies..."	AhmadiAhangar et al., 2019
	"Most microgrids today are basic, one-generator affairs, but more complex microgrids are popping up all over."	Roberts & Chang 2018
	"As the number of distributed generation options expands, microgrids are becoming more complicated."	Krueger, 2020
	"Today's high proliferation of distributed energy resources (DERs) often makes microgrids more complex than in the past."	Nordloh, 2018
	"A wide range of research works in different aspects of microgrids, including control, protection, and optimal structure for energy management, shows that microgrid systems will become more and more complex and selective according to the needed applications."	Sechilariu & Locment, 2016: 30
	"Since the microgrid technology develops, the microgrid system becomes more and more complicated."	Liu et al., 2014: 933
	"As they grow in number and complexity, microgrids will require sophisticated digital automation and smart management in order to become reliable alternatives to the conventional grid. Today's high proliferation of DERs often makes microgrids more complex than in the past."	IEEE, 2020
	"Multi energy coupling also complicates the plan and operation of microgrids. Firstly, coupled components are much more complicated, causing it hard to control. Secondly, one network operation may influence another network, and the coordination of different network are required."	Suyanto & Irawati, 2017: 162
	"The complexity of Microgrid Energy Scheduling (MES) is increasing with the integration of Electric Vehicles (EVs) and Renewable Generations (RGs). Moreover, it is challenging to determine optimal scheduling strategies to guarantee the efficiency of the microgrid market and to balance all market participants' benefits."	Fang et al., 2020
	"In a MG (microgrid), energy management will be more complex and difficult if the DER includes two or more types of resources."	Wang, Mao, & Nelms, 2015
Interactions between systems	"Increasingly, today's electric power grids are interacting with microgrids and in more complex ways."	Rys, 2019

PAPER THREE

TECHNOLOGY INSTITUTIONALISATION: THE INTERPLAY OF MICRO AND MACRO MECHANISMS AND FIELD-LEVEL INFLUENCES

ABSTRACT

I develop a process model of technology institutionalisation that incorporates macro, field, and micro mechanisms and the interaction effects between them. The model centres on the concept of technological fields, which are structured around the production, use, definition, and control of a specific technology, in addition to organisational fields. I propose to apply the notion of a technological field to address the neglected role of materiality in institutional processes. I address the call for more multi-level approaches to examine the institutionalisation process by incorporating micro, organisational and technological field, as well as isomorphic macro-level mechanisms into a model of technology institutionalisation. I emphasise the need for institutional theorists to engage more with technology as an independent institution considering its unique characteristics and importance for organisations. Further, the lack of focus on materiality in institutional theory is addressed by conceptualising technology as an institution and emphasising the moderating role of the technological field in the institutionalisation process.

Keywords:

Multi-Level technology institutionalisation model; Technology as an institution; Technological field

1. INTRODUCTION

Technology is everywhere. The global economy and organisations increasingly rely on technologies. One that has gained significantly in importance over the last decades is information technology (IT). Organisations collect and use more data than ever to improve their decision-making (George et al., 2014) and require IT to manage the immense data volumes. Orlikowski & Barley (2001) addressed already almost 20 years ago the need for organisational scholars to give more attention to technology. Neo-institutional theory, being still a novel perspective to be applied to information technology (IT), provides a rich and diverse conceptualisation of technology as it explains the role of institutions in technology innovation (King et al., 1994) and offers insights into phenomena that are not sufficiently explained by economic-rationalist models (Currie, 2011). Given the increasing reliance on technologies (Castelo & Lehmann, 2019; Grissinger, 2019), it is surprising that the conceptualisation of the technology institutionalisation process has been given little attention by management scholars and new institutionalists (Currie, 2011; Zucker, 1991). Fountain (2001) argues that the role of information technology (IT) needs to be better conceptualised and accounted for by institutional theory. The author emphasises the importance of information technology for organisations and the necessity to apply an institutional perspective to this phenomenon (Fountain, 2001: ix).

In order to better understand the evolution of microgrids, this paper attempts to develop a model of institutionalisation applicable to all technologies. I will draw primarily on the literature on information systems (IS), as this is the literature that has most explored institutionalization. This conceptual study develops a framework for thinking of technology institutionalization as a process driven by interacting micro, specific field, and macro mechanisms. The literature in institutional theory has already uncovered a plethora of mechanisms through which institutionalisation in general occurs (Davis & Marquis, 2005; Schneiberg & Clemens, 2006) but scholars acknowledge it is difficult to compare and differentiate how these mechanisms operate because of the range of empirical contexts in which this research was conducted (Li, 2017). Scott (2014: 151), in his review of institutionalisation mechanisms, has likewise already proposed that there are often several mechanisms that "interact with and reinforce each other" within institutionalisation processes, but this insight operates at a general level rather than helping to explain the institutionalization of new technologies in organisations and society.

To address these limitations in our understanding, the overarching research question of this paper is: *How does a technology become an institution?* The more precise research question is: *How can technologies become institutionalised through an interplay of macro and micro institutional mechanisms and how do field-level mechanisms influence this process?* I will first provide a detailed explanation as of why technology is conceptualised as an independent institution by also defining institutions and institutionalisation in general, to then introduce technology institutionalisation processes. This is followed by an analysis of the micro and macro mechanisms of technology institutionalisation. The concepts of organisational and technological fields and their respective mechanisms, which are relevant for technology institutionalisation, are presented. Finally, the multi-level technology institutionalisation model is explained, followed by a discussion and future research directions.

The key contribution of this paper is to highlight the importance of specific organisational and technological field-level mechanisms in models of technology institutionalisation. Furthermore, I argue that these differentiated field-level mechanisms also moderate macro level institutional mechanisms, the coercive, normative, and mimetic pressures (DiMaggio & Powell, 1983) that identify forces or motives for processes of institutional change (Beckert, 2010; Scott, 2014).

A multi-level perspective on technology institutionalisation

For the purpose of this study, I differentiate between macro-level forces in form of isomorphic pressures and technological- and organisational field-level mechanisms. Here it is argued that focusing on mechanisms specific to the organisational and technological field is a way to improve our understanding of the technology institutionalisation process. It allows us to differentiate field level mechanisms that relate to specific services, products, and technologies from larger isomorphic macro mechanisms. The focus on smaller distinct subfields, such as the technological field, is based on more recent studies that recognise that larger fields are not necessarily uniform but can be characterised by heterogeneity (see Quirke, 2013 for an overview).

Technological fields and related mechanisms relate to certain technologies and their characteristics and can thus be described as subfields.

2. TECHNOLOGY AS INSTITUTIONS

Before discussing the view of technologies as institutions, it is important to define the term 'technology'. I refer to technology as a "set of pieces of knowledge, both directly 'practical' (related to concrete problems and devices) and 'theoretical' (but practically, applicable although not necessarily already applied), know-how, methods, procedures, experience of successes and failures and also, of course, physical devices and equipment" (Dosi, 1982: 151-152).

This paper contributes to neo-institutional theory and I refer to Jepperson's (1991: 145) definition of institutions as "social patterns that, when chronically reproduced, owe their survival to relatively self-activating social processes". The institutionalisation process leads to taken-for-granted and standardised patterns of activities that are ultimately viewed as objective and exterior (Zucker, 1977). Zucker (1977: 728) further refers to institutionalisation as "both a longitudinal process and a property variable". For the purpose of this study, I will focus on institutionalisation as a process. It is important to differentiate between institutionalisation and diffusion as the former ultimately leads to a permanent state of things whereas the latter refers to how things are spreading (Colyvas & Jonsson, 2011: 28). Institutions represent stability but this does not entail that this stability cannot fade over time when no effort is made to maintain it (Zucker, 1988). The process that describes the weakening of institutions is referred to as deinstitutionalisation (Scott, 2014: 166).

Jepperson (1991) was one of the first who conceptualised information technology as an institution. Using DOS as an example he argued that the software is a technological institution as it provides a constraining set of rules that dictate how it interacts with computer hardware. The example of DOS also illustrates that a technological institution does not need to be visible to be powerful as DOS remained an integral building block for other applications and operating systems such as older versions of Microsoft Windows (Pinch, 2008). The taken-for-granted usage and frequent discussion of technology in everyday life without questioning its legitimacy are two central arguments to conceptualise technology as an institution (Wiredu, 2012). This consideration helps to explain how a technology exercises an independent causal influence (Wiredu, 2012) and emphasises the importance to understand the institutional field of the respective technology (Avgerou, 2000; 2002). Avgerou (2000) follows Jepperson (1991) and draws on the conceptualisation of technology as an institution in its own right. However, Avgerou's (2000) paper has mainly been cited in information systems research studies with few exceptions (e.g. Volkoff et al., 2007). This is exemplary for information systems studies drawing on institutional theory with organisation studies rarely doing the reverse (Orlikowski & Barley, 2001).

Orlikowski (2007) argues that organisational research could acknowledge the importance of technology more to reduce the risk of taking it for granted and thus to limit its theorisation. Barad (2003: 801) refers to this as "…the only thing that does not seem to matter anymore is matter". Social theory needs to address the materiality that can be found in the things the social world is built of and in the social action that is mediated by materiality. She concludes that technologies must be institutions, bearing in mind that institutions themselves are made from things and people (Barad, 2003).

Comparing IT innovation with organisational practice, Avgerou (2000:235) refers to both as institutions but with distinct mechanisms, legitimating elements, and levels of institutionalisation. She concludes while IT institutionalisation is well advanced and self-justified, established organisational structures and practices are often in a process of deinstitutionalisation due to actors challenging their legitimacy (ibid.). The technological and organisational institutionalisation processes are intertwined but do not run in parallel (ibid.). While there might be an increasing confidence and resulting taken-for-grantedness in the capabilities and progress of technology representing an institutionalisation process, there might be organisational structures that are viewed as less convincing and thus losing legitimacy reflecting a deinstitutionalisation process. The institutional substance of technology in general and information technology in particular can be argued based on its recognised value for society and the existence of dedicated experts, regulations, and professional organisations focused on technology development and policy (Avgerou, 2000:237). The IT diffusion process is sustained not only based on rational arguments but because professionals as well as people in their personal lives have started to place their trust and hopes on the technology (ibid). Wiredu (2010: 99) agrees with Avgerou (2000) in stating that "both, IT and bureaucracy are distinct institutions with their own orders".

Three interrelated technology institutionalisation phases have been identified. First the "development of IT, communications, and related services industries". Second, "government policy and legislation regarding R&D, production and use of technologies" and third, "the development of the IS [information systems] function within 'user' organisations" (Avgerou, 2000: 238).

Munir & Phillips (2005) also found that a technology can become an institution through processes of social construction. When a technology is implemented in the workplace it is often perceived as an institutional property. The technology users' behaviour is mediated through norms, interpretive schemas, and resources that are embedded in it. Information technology with its institutionalised properties shapes human action by supporting or constraining specific outcomes (Orlikowski & Robey, 1991: 161). Grant (1988), for example, found in her study on computerised performance monitoring systems that characteristics of the information technology affected the work life by, for example, shifting supervisory responsibilities to more qualitative work aspects.

In this study I suggest that classifying technologies as institutions allows for a better understanding of how the institutionalisation of technology differs from organisational practices. It is proposed that technology institutionalisation is a process that is driven by multiple micro-, organizational/technological field, and broad macro mechanisms that interact with each other. This perspective further emphasises the importance of viewing technology as a theoretically relevant element with its distinct institutionalisation mechanism and not solely as the empirical context.

3. THE TECHNOLOGY INSTITUTIONALISATION PROCESSES

The social process by which institutions are produced and reproduced and by which individuals acknowledge a common definition of social reality is referred to as institutionalisation (Phillips et al., 2004; Scott, 1987). Studying this process means to focus on the "creation and transmission of institutions", how they are resisting change, and maintain the status-quo (Zucker, 1991: 104). Institutionalisation processes can take place at several levels and institutionalised practices are "infused with value beyond the technical requirements of the task at hand" (Green, 2004: 657). A simplified but broadly accepted description of the institutionalisation process consists of objects that are first recognised, then sparely accepted, to finally being broadly diffused and established within a field (Lawrence et al., 2001: 626).

Green (2004) found that at pre-institutionalisation stages, the technology still requires justifications and thus taken-for-grantedness is low, whereas at later stages leading to full institutionalisation, these justifications disappear and taken-for-grantedness is high. There are two processes of interplay which reinforce technology institutionalisation: (1) organisational processes shaping the technology and (2) the use of technology that shapes the culture and functioning of the organisation and leads to changes in them (Baptista, 2009). The institutionalisation makes the technology a natural extension of the user, ultimately becoming forgotten, invisible, or as Heidegger phrased it "ready-at-hand" (ibid.; Damsgaard & Scheepers, 2000). An institutionalised information technology is then becoming 'part of the furniture' (Currie, 2004) and is considered a taken-for-granted tool that is unnoticed and is no longer seen as an innovation (Silva & Backhouse, 1997). Such institutionalised information technology is only becoming visible when it stops functioning (ibid.) with the invisibility being an indicator for the level of institutionalisation (Baptista, 2009). When practices and procedures linked with the technology have become routines that also are organisational habits then the technology can be considered as institutionalised (Silva & Backhouse, 2003). It has been found that there are significant shortcomings in the literature regarding the processes supporting technology institutionalisation in organisations (Bansler et al., 2000; Baptista, 2009). Following the perspective of Zucker (1987), technology becomes institutionalised when it appears invisible and its use becomes unnoticed (Silva and Backhouse, 1997; Damsgaard & Scheepers, 2000). A considerable amount of literature has studied the institutionalised rules that reveal themselves in how people make decisions, pursue behaviours, and frame issues (Jepperson, 1991; Powell & DiMaggio, 1991; Scott, 1995; 2001). The conformity to these rules or existing institutions and its effect on organisations has been widely studied (Arthur, 1989; David, 1985; North, 1990) but institutional theory has paid relatively little attention to the institutionalisation process, how these institutions come into existing (Garud et al., 2002). The institutionalisation process needs to be better understood to comprehend why and how individuals rely on pre-existing institutions and how institutions can be formed for a future with novel technological requirements (Garud et al., 2002). Garud and colleagues (2002) focused on the actors' role in the creation of institutions. In general, there are two perspectives to examine this process:

a rational economic view and an institutional theory perspective to investigate how actors build their targets and procedures into the developing institution (Fligstein, 1999; Garud et al., 2002; Hirsch, 1975; Meyer & Rowan, 1977). This shaping of emerging institutions constitutes “acts of institutional entrepreneurship” (Garud et al., 2002: 196; DiMaggio, 1988) which becomes more important with new technologies that break open the institutional black box with its taken-for-granted assumptions (ibid., 2002). Technologies require their separate institutional space with “rules that govern the production, distribution, and consumption of associated artifacts” (Garud et al., 2002: 197). Technological fields are part of the institutional space that shapes them (Garud & Jain, 1996) with technological standards being an integral part of this environment (Garud et al., 2002: 197).

Common technological standards are often required for users to exchange products in a marketplace by offering the necessary framework (Garud & Karnøe, 2003; Garud & Rappa, 1994). Firms can benefit from influencing common standards as they can build characteristics of their technology into evolving institutional structures (Garud et al., 2002). Firms operating in information technology fields that produce distinct components of larger technological systems are particularly able to benefit due to network externalities (Katz & Shapiro, 1985) and increasing returns (Garud et al., 2002; Shapiro & Varian, 1999). Meyer & Rowan (1977: 344) argue that institutionalised technologies function as “myths”. Technical processes “become taken-for-granted means to accomplish organisational ends”. Institutionalised techniques provide an organisation with legitimacy and their use reflects responsibility but not efficiency (Meyer & Rowan, 1977). Technologies, and information technologies in particular, play an integral part in enabling organisational stability (Baptista et al., 2010; Czarniawska, 2008). Tolbert and Zucker (1983) found that early adopters of technology make decisions based on technical factors and later adopters follow institutional pressures to gain legitimacy (Lawrence et al. 2001).

Baptista (2009) and Baptista et al. (2010: 177) identified, using empirical data, six categories of characteristics that describe institutionalised technologies: representative, formalised, functional, importance, familiar aesthetics, and ease of use. Their typology focuses on socio-material properties of technology. In the case studied, the technology (intranet) and users were so deeply intertwined that a separation seemed impossible. The first group of characteristics are *representative* and the background to this concept is that institutionalised technology is perceived as exterior or independent to individuals' or other stakeholders' interests (Baptista et al., 2010). The second group is referred to as *formalised* and identifies that "institutionalised technology becomes part of the formal functioning of organisations" (Baptista et al., 2010:177). The technology gains legitimacy as it is seen as the correct way of doing things (Baptista et al., 2010). The third group of features is called *functional*, describing institutionalised technology characterised by being embedded and aligned with the organisation's functioning and as such offers an accepted method for doing things (ibid.). The fourth set of features is grouped into the term *importance* and states that a technology is institutionalised when it is increasingly integrated in business processes and used for important tasks (ibid.). The fifth group is called *familiar aesthetics* referring to institutionalised technology as being familiar to users who perceive it as a feature of everyday life (ibid.; Schutz, 1962). The sixth category of characteristics that describe an institutionalised technology is called *ease of use* and refers to the technology becoming easier and natural to use and thus usage becomes intuitive (ibid.; Davis, 1989).

3.1. The three-stage technology institutionalisation process

An important aspect in understanding and conceptualising the institutionalisation process are the determinants of changes in institutionalisation levels (Tolbert & Zucker, 1996). Tolbert and Zucker (1996) define technology institutionalisation as a three-stage process consisting of habitualisation, objectification, and sedimentation to emphasise the variability in institutionalisation levels. The authors built their multistage model on the notion of 'objectification' identified by Berger and Luckmann (1967). The authors define an institution as a "reciprocal typification of habitualized action by types of actors" (1967: 72). Reciprocal typification refers to "the development of shared definitions or meanings that are linked to these habitualised behaviours" (Tolbert & Zucker, 1996: 180). These behaviours are habitualised until actors can evoke them with minimal decision-making effort (ibid.). The meanings associated with an habitualised action are generalised and thus are independent of actors with Zucker (1977) referring to this process as 'objectification' (ibid.). Based on these insights there are at least two sequential processes involved in the institutionalisation process: habitualisation and objectification with the former referring to the formation of problem-solving behaviours and their association with specific stimuli and the latter referring to the development of common social meanings related to these behaviours (Tolbert & Zucker, 1996). Exteriority, as the third aspect of institutionalisation, refers to institutions that are "experienced as possessing a reality of their own, a reality that confronts the individual as an external and coercive fact" (Berger & Luckman, 1967: 76). Sedimentation describes the processes through which actions obtain exteriority (Tolbert & Zucker, 1996). Objectification and exteriority were found to be positively related to the degree of institutionalisation (Zucker, 1977). Further, institutionalisation was also positively related to transmission, maintenance, and resistance to change of actions (ibid.). Nelson and Winter (1982; 2009) found that the more institutionalised routines are, the easier they are transmitted to new employees. Transmission increases the exteriority of behaviours making them more institutionalised and thus facilitating further transmissions (Tolbert, 1988; Tolbert & Zucker, 1996). The three-stage process described by Tolbert and Zucker implies different levels of institutionalisation are possible and thus patterned behaviours can also vary in their degree of embeddedness, in terms of objectivity and exteriority, in a social system (ibid., 1996).

a. ***Habitualisation***

The habitualisation process produces technologies that can be considered as *pre-institutionalised*. At this stage, there may be relatively few adopters who likely are interconnected but use different implementation forms. Thus, there is no formal theorising (Strang & Meyer 1993) of these structures which will remain largely unknown among non-adopters (Tolbert & Zucker, 1996). Adoption of a technology can be predicted according to its level of technical and economic viability for an organisation (Anderson & Tushman, 1990; Leblebici et al., 1991) and by the inner political arrangements of organisations that influence their receptiveness for change (March & Simon, 1958; Tolbert & Zucker, 1996).

b. ***Objectification***

Objectification refers to the processes by which organisational actors achieve some degree of consensus regarding the value of a technology. Based on this consensus the adoption process advances (Tolbert & Zucker, 1996). Consensus is achieved through either a risk assessment of adopting the new technology using a variety of sources or through so called 'champions' which are people with a "material stake in the promotion of the structure" (DiMaggio, 1988, In: Tolbert & Zucker, 1996: 183). To achieve consensus among adopters, champions need to complete two tasks of theorisation. The first refers to specifying a general organisational problem for which a local innovation is a solution and the second involves the justification of the innovation as a "solution to the problem on (either) logical or empirical grounds" (Tolbert & Zucker, 1996: 183). Objectification is partially a result of competitor monitoring by organisations and their aim to improve their relative competitiveness (ibid.). The number of organisations adopting a certain structure positively influences the likelihood that decision-makers believe that the benefits of adopting a new structure outweigh the costs (ibid.). This argumentation is in line with models of sequential decision-making (Banerjee, 1992) which assume that decision-makers use the choices of others as well as their own assessment to gain information to make the best decision. Thus, the more adopted a given structure becomes, the more likely decision-makers follow the choice of others, and the less they trust their own assessment (Tolbert 1985; Tolbert & Zucker, 1996).

After the objectification process, a technology is relatively widely diffused and can be described as *semi-institutionalised*. The motivation for diffusion moves from imitation to a normative base, reflecting an increase in theorisation of technologies which leads to reduced variance of technologies across organisations (Tolbert & Zucker, 1996). Such technologies have a higher survival probability than those not yet institutionalised but they are not excluded from distinction. Thus, due to their relatively short history, technologies at that stage have a fashion-like quality with some normative acceptance but adopters are cautious with regard to their untested quality and effectiveness (ibid., 1996).

c. *Sedimentation*

Sedimentation, or *full institutionalisation* (Greenwood et al., 2002), describes the stage at which a technology is completely spread within the group of actors that was theorised as suitable adopters. Those technologies are characterised by their high stability and at this stage the tendency of actors to independently evaluate the technology declines (Tolbert & Zucker, 1996). In order to understand the sedimentation process, it is central to identify factors affecting the degree of diffusion and long-term stability of a technology. An example are actors who are negatively affected by the technologies and who can collectively rally against them (ibid.: 184).

Sedimentation as a stage can be destabilised when there is no clear link between the innovation and desired outcomes. If the impact of an innovation cannot be demonstrated, then the development and promotion of alternatives with a similar purpose leads to the replacement of the innovation (Abrahamson 1991; Tolbert & Zucker, 1996). Full institutionalisation therefore depends on the interplay of several factors such as relatively little resistance, cultural support and promotion, and a positive relationship with desired outcomes. Opposing groups can limit the diffusion of an innovation and to counteract destabilising tendencies it is necessary to have demonstrable benefits and continued promotion (Tolbert & Zucker, 1996; Zucker, 1988). Heugens and Lander (2009), using a meta-analysis, shed light in the structure versus agency debate in institutional theory. Structuralists argue that social structures such as isomorphic pressures determine organisational behaviour whereas agency theoreticians stress that such social structures are only platforms for organisational actors and increased institutionalisation may eventually lead to change (Giddens, 1979; Schneiberg, 2005; Washington & Ventresca, 2004). Heugens and Lander (2009) showed that all three isomorphic pressures identified by DiMaggio and Powell (1983) have a homogenising effect on organisations, emphasising the effect of social structure on organisational behaviour.

4. MICRO AND MACRO MECHANISMS OF TECHNOLOGY INSTITUTIONALISATION

The literature in institutional theory has acknowledged the importance of mechanisms through which institutionalisation occurs (Davis & Marquis, 2005; Schneiberg & Clemens, 2006) but they have mainly been left unstructured and thus hard to compare and differentiate (Li, 2017). Ylikoski (2012: 22-23) identified four characteristics of mechanisms: First, they are “identified by the kind of effect or phenomenon” they create. Second, they are an “irreducibly causal notion” referring to “the entities of a causal process that produces the effect of interest”. Third, mechanisms have both a structure and fourth, a hierarchy. Anderson and colleagues (2006) argue based on Weick (1989) that the central aspect of theory construction is to explicitly explain the linkage between an input and an output to reveal the transformation process. Focusing on mechanisms for theory construction is therefore a promising endeavour as it also puts the emphasis on the bigger picture of a phenomenon instead of focusing on linkages between individual variables only (Anderson et al., 2006).

Scholars have recognised the importance of including multiple levels of analysis when examining constructs (Klein et al., 1994) or organisational phenomena (Kozlowski & Klein, 2000). The institutionalisation of technology is driven by both macro and micro level mechanisms. A multi-level analysis to study technology institutionalisation has therefore been suggested (Thornton et al., 2012.). The majority of studies examining the institutionalisation process focus on the role of macro level mechanisms, in form of institutional isomorphic pressures (Zucker & Schilke, 2020). This, however, has not been the case in early studies of institutional theory (e.g. Zucker, 1977) which understood the importance of examining micro mechanisms in explaining institutionalisation processes (ibid., 2020). The macro-perspective in isolation cannot sufficiently explain the overall institutionalisation process. It is important to also understand micro-level mechanisms and the interplay between macro and micro mechanisms (Thornton et al. 2012) and treat them as complementary perspectives to the sole focus on macro mechanisms (Barney & Felin, 2013). Scott (2014: 151), in his review of institutionalisation mechanisms, concludes that there are often several mechanisms involved that "interact with and reinforce each other" with institutionalisation processes occurring on multiple levels. Here mechanisms are a defined "class of events" (McAdam et al., 2001: 24) that influence the institutionalisation process. A multi-level analysis considering multiple mechanisms to study technology institutionalisation has therefore been suggested. This requires the identification of relations between variables at multiple levels (Rousseau, 1985: 8). I focus here on the interplay between macro and micro mechanisms for technology institutionalisation and how technological field-level mechanisms moderate this interaction.

4.1. Micro mechanisms: people interacting with technologies

A complementary approach to the macro perspective and only recently rediscovered is the micro-level approach to the analyses of institutionalisation processes (Zucker & Schilke, 2020). While a micro-level perspective to analyse institutions is not new (e.g. Berger & Luckmann, 1967; Zucker, 1977), most studies in organisational research have focused since on the organisation and field-level (Powell

& Colyvas, 2008; Schneiberg & Clemens, 2006). Micro mechanisms consider the role of individuals in the development of institutions (Zucker & Schilke, 2020) and how their interactions shape and are shaped by institutions (Thornton et al. 2012). A number of institutional theorists have rediscovered the importance of examining the micro-foundations of institutions (e.g. Gehman et al., 2016; Powell & Colyvas, 2008). The micro perspective offers valuable insights in the longitudinal creation and maintenance of technology through institutional work (Lawrence & Suddaby, 2006). Zucker (1977: 742) in her seminal micro-level study found that the degree of institutionalisation is positively related to the "resistance to change through personal influence". She showed with her study the importance of considering the micro-foundations to explain the institutionalisation process. Scott (2008) argues that organisations are active players able to strategically and innovatively respond to institutional pressures. The literature examining the efficiency and value in technology institutionalisation or the institutional elements that influence this process for efficiency and legitimacy purposes has been very limited (Pishdad et al., 2014). The micro-level perspective focuses on the emergence of patterns of behaviour and shared meanings in organisations and views institutionalisation as a source for reproduced institutional behaviour and not as the result (Baptista, 2009). At the micro level, technology institutionalisation occurs through the continuing embedding of technologies in the practises and routines of individuals leading to socially constructed behaviour that becomes gradually more stable (Pishdad et al., 2014). Institutional entrepreneurship, a notion introduced by DiMaggio (1988), investigates the role of individuals in changing existing or creating novel institutionalised practices and technologies (Battilana et al., 2009). The important role of the individual in the institutionalisation process has been emphasised by several studies. Managers were found to influence the diffusion of practices through their rhetoric (Green, 2004; Green et al., 2009). Technology institutionalisation has been found to be driven and hindered by 'organizing visions', which are community ideas of a technology (Currie, 2004; Swanson & Ramiller, 1997: 460) as well as by the power of individuals (Silva, 2007).

Baptista (2009) studied the institutionalisation of an information technology (intranet), applying a micro-level approach. Technology institutionalisation is explained as a bottom-up process driven by the growing familiarity of users with the technology, the technology's increasing role in users' routines and habits, and the users' perception that the technology is embedded in the organisation's formal functioning (Baptista, 2009). The process increases the compatibility of the technology with the organisation and helps the organisation to adapt current work practices to the potentials of the new technology. The micro institutional mechanisms driving technology institutionalisation the study identified are: governance, senior support, business alignment, perceived importance and benefits, familiarity, usefulness, and ease of use (Baptista, 2009: 317). Technology institutionalisation is viewed as a bottom-up process that builds on fluctuations in behaviour at the micro-level. The process creates institutionalised actions through integrating the technology in the traditions and routines of actors (Baptista, 2009). When micro-level actors and higher field and macro levels are viewed as separate and independent, an explanation of how lower-order actions and structures constitute macro-level structures becomes impossible (Hoffman & Ventresca, 2002). It therefore has been suggested to conceptualise the micro-macro relation as a process of institutionalisation in which "habitualised actions and intentions are transformed into macro-level structure" (Li, 2017: 4).

4.2. Macro mechanisms

The macro perspective considers the environment as central to creating institutionalised behaviour. Meyer and Rowan (1977) apply this approach and introduce isomorphism to explain the diffusion of practices across organisations. Institutionalised practices move across organisations promoting the convergence of practices through the three types of institutional pressures (DiMaggio & Powell, 1991). The macro level explains institutionalisation by focusing on an organisation's ability to achieve legitimacy (Deephouse & Suchman, 2008; Lawrence et al., 2001). Organisations that incorporate institutionalised elements protect themselves from having their legitimacy questioned (Meyer & Rowan, 1977: 349) and therefore efforts are made to create and maintain legitimacy (Dillard et al., 2004). Institutions have the ability to influence organisations to "adopt practices consistent with institutional practices" (Greening & Gray, 1994: 471). In this sense the "adaptation of an institutional practice by an organisation" is referred to as isomorphism (Dillard et al., 2004: 509). The macro-level institutionalisation mechanisms are "coercive, normative, and mimetic isomorphic processes" (DiMaggio & Powell, 1983: 147) through which an organisation forms, preserves, and changes its rules, ideals, and practices (Pishdad et al., 2014). Coercive pressures stem from political influence and legitimacy issues. Mimetic pressures result from uncertainty while normative pressures stem from professionalisation (DiMaggio & Powell, 1983). In general, isomorphic processes are regarded as legitimacy-providing (Deephouse & Suchman, 2008) and therefore as desirable (Suchman, 1995). To comprehend the institutionalisation process of technology it is also important to consider the effects of institutional change and deinstitutionalisation (Claig & Bailey, 2007; Greenwood et al., 2002). An increase in institutional isomorphic pressures initiates the institutionalisation process but a decrease leads to deinstitutionalisation, a process reflecting the destruction of existing and establishment of new institutions (Pishdad et al., 2012; Seal, 2003).

Pishdad et al. (2012) explain the technology institutionalisation process using the concept of isomorphic pressures. Regarding coercive isomorphism, an organisation adopts and routinises a technology to conform to the requirements of a more powerful firm in order to maintain business relationships, have access to resources, or make transactions more efficient (Delmestri, 2007; DiMaggio & Powell, 1983). The progressive use of a technology can be explained by normative isomorphism. In this case, a technology is adopted to avoid a damage to legitimacy from the perspective of the industry and other institutions. Also, if a technology is frequently used by an organisation's supplier and customer, then the organisation might become aware of the technology and adopt it itself. Mimetic isomorphism explains the adoption and implementation of a technology with the desire of organisations to follow the actions of competitors in the same industry (Scott, 2008). An organisation's perception of these institutional pressures will affect its interpretation of its technology adoption intention (Pishdad et al., 2012). Institutionalisation processes at the macro level need to be repeated at the micro level to avoid substitution by innovations which demonstrates their intertwining of the two levels (Zucker, 1988 In: Baptista, 2009).

4.3. The interplay between micro and macro

It can be claimed that cross-level studies are not particularly attractive to institutionalists due to their difficult realisation. However, considering that institutional stability and change, being central issues in institutional theory, are the result of cross-level interactions (Barley, 2011), then the lack of attention to level issues is surprising (Bitektine & Haack, 2015). It is essential to consider the interplay between levels to understand the micro-level processes that create, change, institutionalise, and deinstitutionalise institutions (Bitektine & Haack, 2015: 49-50), field level processes specific to a technology, and macro-level institutional processes. The hierarchical structure of mechanisms means that while mechanisms at one level assume the presence of certain entities, the existence of lower-level mechanisms to explain them is also expected (Ylikoski, 2012: 23). Institutionalisation can also be described as the process by which micro-level actions and intentions are transformed into "macro-level structures and objective meaning systems" (Li, 2017: 522).

5. THE MISSING PERSPECTIVE: TECHNOLOGICAL FIELD-LEVEL MECHANISMS OF INSTITUTIONALISATION

This study argues that a focus on technological fields in addition to organisational fields adds to the predictive power of a technology institutionalisation model. Several studies in institutional theory have focused on within-field variability in isomorphic processes (Boxenbaum & Jonsson, 2008), examining the level of homogeneity (DiMaggio & Powell, 1983) and conformity (Oliver, 1991) of organisations in a field. The influence of between field-level mechanisms on isomorphic processes has, however, been examined less. It has been found that field-level mechanisms have a moderating influence on macro-level institutional pressures (Heugens & Lander, 2009). Several explanations of the directionality of the moderating effect of field-level factors on isomorphic processes have been suggested. The pull factor of isomorphic forces has been argued to increase when professionalization increases, state interactions are frequent, and the number of known alternatives for organising in a field is low (DiMaggio & Powell, 1983: 155-156). Further, it has been suggested that fields with weak boundaries experience a lower effect of these forces on isomorphism (Greenwood & Hinings, 1996: 1028-1031).

Heugens and Lander (2009) also found that organisational field–level factors actively moderate isomorphic processes with fields in which there is high interaction between organisations and state agencies experiencing stronger isomorphic pressures (Heugens & Lander, 2009). Thus, a further exploration of micro foundations of diffusion mechanisms and processes is useful (ibid.). The authors suggest focusing future research on the 'processual dimension of isomorphism' to better understand how organisations experience, interpret, and learn from them (Heugens & Lander, 2009: 76). Also, studies contributing to a better understanding of how field-level isomorphic processes influence collective organisational action would be a further opportunity for research (ibid.; Lee & Pennings, 2002). There have been several explanations for the existence of collective actions underlying isomorphic processes such as viewing them as strategies for minimising shared regrets (Landman, 1993), strengthening collective identities (Hardy et al., 2005), or a joint need to avoid negative feelings arising from nonconformity (Scheff, 1988). Such micro-sociological processes can connect the concept of isomorphic pressures to organisational actions, deserving more attention by institutionalists (Mizruchi & Fein, 1999; Heugens & Lander, 2009). Following Heugens and Lander (2009) it is argued here that applying the concept of a technological field, with its focus on the technology of interest, offers important opportunities in identifying mechanisms that have a direct influence on technology institutionalisation, act as moderators in isomorphic processes and specify micro technological mechanisms.

Pishdad et al. (2014: 6) found that interactions between macro environmental institutional mechanisms and organisational and technological institutional logics may be actively managed to increase an organisation's legitimacy and performance. The technological field specifies the technological aspects that are relevant for the institutionalisation process. By using the concept of the technological field as a moderator as well as direct influence in the technology institutionalisation, highlights the material dimension such as design considerations in this process.

Central to technological fields are technological systems which provide utility to users through an interacting set of components (Garud et al., 2002). The compatibility among system components, achieved through a design reflecting a common standard, together with the performance of the components themselves determine a system's overall performance (Garud et al., 2002). The existence or non-existence of a design reflecting a common standard has a direct impact on innovation within a technological field. Firms operating in a technological field with no common standard have difficulties to coordinate their innovation activities whereas interdependent firms operating in a field with common standards might be hindered in innovating due to the fear of introducing incompatibilities (Brunsson & Jacobsson, 2000; Garud et al., 2002).

The technological field also specifies the technological aspects, micro-level mechanisms, that are relevant for the institutionalisation process. The concept emphasises distinct mechanisms relevant for the institutionalisation of technology and is therefore complementary to the concept of an organisational field. Both concepts describe field-level factors, but the technological field is defined around the development and use of a technology which allows for the identification of other relevant institutionalisation mechanisms. We have learnt that a technology is more likely to become institutionalised when it is compatible with a specific standard in the technological field. This standard deviates from the standard defined in the organisational field concept. It is argued here that both the organisational and technological field mechanisms have a moderating influence on macro-level institutional pressures but also exert a direct influence on the institutionalisation process of technologies.

5.1. The technological field

Friedman (1994a: 139) introduced the concept of a technological field, which he defines as a "social space within which structuring of people and institutions occurs in relation to a bundle of techniques." He defines the information technology field as the "social space structured around the production, use, definition, and control of information technology" (Friedman, 1994b: 371). Information technology (IT) is a collection of "techniques that relate to computer based administrative or information-handling systems" (ibid. 1994a: 139). Institutions and individuals can belong to several fields as for example an information systems (IS) specialist can also be a mathematician and an organisation using IS can also use optical technology (Friedman, 1994a). Information technology serves as the underlying technology for information systems and includes the bundle of techniques for "developing, implementing, and maintaining computer-based information systems" as well as the "design and characteristic materials used in computer hardware, software, and peripheral equipment" (Friedman, 1994b: 371). In a technological field, a shared set of technologies is the focus of organisational activity and thus the field refers to a community of organisations that develop, use, regulate, or exploit a technology or set of technologies while sharing a common meaning system and being in frequent interaction among each other (Granqvist, 2007: 9). There are alternative technological trajectories within a new technological field that compete in a challenge for dominance (Suarez, 2004; Garud et al., 2002). The organisation and dynamics of the technological field determines the firms' negotiation process leading to either cooperation or competition. The population of technological fields consists of research communities in specific disciplines and firms operating along the value system of the product-market domain (Suarez, 2004: 279) such as scientists, government officials, or entrepreneurs (Grodal, 2007).

The meanings of artifacts and patterns of interaction within a technological field develop through a negotiated process (Bijker et al., 1987). Studies that apply the concept of a technological field to institutionalisation processes need to choose how broad (e.g. microgrid technology) or narrow (e.g. microgrid control systems) they want to define it as this will shift the focus from higher generalisability to higher specificity (Bergek et al., 2005).

5.1.1. Technological field and institutionalisation of technologies

The strategic relevance of a technology (or other resource) depends on firm related characteristics with complementarity being a central issue (Makadok & Coff, 2002). It can be concluded that a technology that is compatible with a specific standard in the technological field is more likely to become institutionalised (ibid.). A wider technical environment that influences the development of information systems functions within organisations is called the information systems (IS) field (Borum et al., 1992). Depending on their specific frames, different actors in a technological field 'enact their realities' (Garud & Karnøe, 2001: 10). The actors' perspective as either a regulator, user, or producer influences their identification and ascription of particular meanings to the objects comprising the technological field and ultimately these meanings become internalised within actors (Garud & Karnøe, 2001: 10). During this process of reality enactment, actors engage in a debate to negotiate the relevance of objects and behaviours, which eventually results in institutionalised practices and meanings shaping the frames and actions of actors. These intersection processes provide shape and meaning to the technological field (Garud & Karnøe, 2001: 10) and lead to the desire for simplicity, resulting in a taken-for-grantedness of meanings and practices (Hughes, 1983, In: Garud & Karnøe, 2001). Actors subsequently become 'embedded in self-reinforcing processes' of the technological field they have contributed to generate (Garud & Karnøe, 2001: 10). The authors (2001: 11) therefore argue that a technological field stabilises through interaction processes between elements of the field which leads to their alignment and mutual reinforcement. The negotiation process gives meanings to objects that constitute the field leading to their provisional stabilisation (ibid.; Levy & Scully, 2007).

5.2. The organisational field

DiMaggio and Powell (1983: 148) describe an organisational field as "those organizations that, in the aggregate, constitute a recognised area of institutional life: key suppliers, resource and product consumers, regulatory agencies, and other organizations that produce similar services or products." This unit of analysis does not solely involve competing firms or networks of interacting organisations but the entirety of relevant actors (DiMaggio & Powell, 1983). Organisational fields must, through a process of structuration, be institutionally defined to exist (ibid.). This process consists of four parts: "an increase in the extent of interaction among organizations in the field; the emergence of sharply defined inter-organizational structures of domination and patterns of coalition; an increase in the information load with which organizations must contend, and the development of a mutual awareness among participants in a set of organizations that are involved in a common enterprise." (ibid.: 148). This definition links micro-level actions to field-level structures, refers to actors as knowledgeable, and suggests that institutions both result from and restrict social action (Barley & Tolbert, 1997). The organisational field is a core concept to institutional theory representing the level between the society and an organisation. It is instrumental to processes leading to dissemination and reproduction of socially constructed expectations and practices (Greenwood et al., 2002; Scott, 1995). Quirke (2013) argues that a field is best defined by organisations facing the same regulatory and environmental factors. The literature moved from describing organisational fields as uniform to acknowledging that fields may be segmented, may contain both diversity and homogeneity clusters, and that subfields within may face different isomorphic pressures (Quirke, 2013).

5.2.1. Organisational Field and institutionalisation of technologies

Technologies diffuse at varying speeds throughout an organisational field (Lawrence et al., 2001: 627). Despite the usual stability of an organisational field (DiMaggio & Powell, 1983; Meyer & Rowan, 1977), fields can undergo change triggered by disruptive events leading to a process of deinstitutionalisation followed by re-institutionalisation (Fligstein, 1991; Jepperson, 1991). Lawrence et al. (2001) define the speed of institutionalisation as the duration an innovation requires to diffuse across an organisational field. Institutionalised practices, rules, technologies, or a combination of them are the outcome of an instance of institutionalisation meaning that they have become and remain diffused throughout an organisational field (ibid.). This defines the stage of legitimation, in which practices or technologies are widely diffused throughout the field but stability, durability, and influenceability of the institution remain unclear (ibid.).

5.3. Distinguishing between technological field and organisational field

A technological field is similar to an organisational field as both comprise a shared set of meanings, with the technological field representing relationship patterns between artifacts and individuals related to a specific product-market (Garud & Karnøe, 2001; Garud et al., 2002) such as microgrids. Despite these similarities, it is argued here that the application of the technological field concept to the analysis of technology institutionalisation enables a better understanding of such processes compared to solely considering the organisational field. The technological field emphasises a focus on the technology and material aspects and thus provides the researcher with a different set of mechanisms that influence the institutionalisation process. In order to understand how a technology is institutionalised, it is important to consider both, the organisational field (e.g. the electric power industry) and the technological field (e.g. microgrid systems). When considering mechanisms specific to an organisational field for the institutionalisation process of technologies, then all "those organizations that, in the aggregate, constitute a recognised area of institutional life: key suppliers, resource and product consumers, regulatory agencies, and other organisations that produce similar services or products" (DiMaggio &Powell, 1983: 148) will be considered. This reflects a substantially larger group that is considered for the technology institutionalisation process i.e. organisations operating in the electric power industry compared to the focus on microgrid technology stakeholders what the technological field considers.

Hargadon and Douglas (2001) emphasised the importance that both individuals and organisations understand a new technology and how to respond to it in order to institutionalise it. The authors found that an innovation's design is at the centre of this process. This design is specific to the technology studied which is reflected by the technological field and not the organisational field characteristics. The specific attention to technological field mechanisms as opposed to solely focusing on the organisational level, gives materiality a more central role within the institutionalisation process. Attributes related to a technology's materiality such as complexity (Sun & Zhang, 2006), design (Garud et al., 2002), and compatibility (Makadok & Coff, 2002) influence its institutionalisation process (see Table 1).

5.4. How organisational and technological field-level mechanisms interact with micro and macro levels

Bitektine and Haack (2015) developed a multi-level model of organisational legitimacy that explains institutional stability and change by describing the communicative and cognitive mechanisms that link individual judgements and higher-level agreements. They approach organisational legitimacy as a judgment (also see Bitektine, 2011), decided by individuals at the micro level and by a group of actors at the field level (Bitektine & Haack, 2015). Their theory suggests that in stable institutional conditions, the legitimacy process is controlled by organisational field level influences that are passed down to the micro level. The legitimacy judgement that is institutionalised at this level creates macro level isomorphism among individual evaluators due to conformity pressures (Bitektine & Haack, 2015). Even those actors who keep relying on their own propriety judgements will apply the taken-for-granted set of norms which results in the same institutionalised judgement (ibid.). However, in situations of institutional change, due to unprecedented events (Greenwood et al., 2002) or institutional entrepreneurship (Maguire et al., 2004), the level of deviant judgements increases which in turn decreases institutional stability. If there is no consensus in the field then organisational field level validity cues are less trusted, leading to a higher reliance on independent judgements (Bitektine & Haack, 2015).

Independent judgements are less influenced by validity and are therefore prone to initiate a change process by questioning the status-quo, illegitimating the current validity judgement, and proposing legitimate alternatives to established technologies (ibid.). Table 1 lists the mechanisms that have been identified to influence the technology institutionalisation process.

Table 1: Technology Institutionalisation Mechanisms

Analytical Level	Mechanism	Description	Reference
Micro			
	rhetoric	"discourse calculated to influence an audience toward some end" (Gill & Whedbee, 1997: 157). Actors influence the legitimacy of technologies by making convincing arguments to validate technologies.	Green et al. (2009)
	organising visions	"a focal community idea for applying IT in organizations" (Swanson & Ramiller, 1997)	Swanson & Ramiller, (1997); Ramiller & Swanson, (2003)
	familiarity	the technology replicates the values and beliefs of the organisation to appear familiar	Baptista (2009)
	usefulness	users acquire an understanding of how to use the technology and recognise new potentials	Baptista (2009)
	governance structure	technology functions are aligned with those of the organisation. The organisational structure dictates the roles and responsibilities for the technology.	Baptista (2009)
	senior support	senior staff support the technology which becomes a central part of the organisation. Internal regulations advocate its use and alternatives are eliminated.	Baptista (2009)
	business alignment	the technology was developed to meet a specific business need and is adapted accordingly	Baptista (2009)
Organisational Field Moderating Factors			
	fields populated by public organisations	isomorphic forces are stronger in "fields populated by public organizations"	DiMaggio and Powell (1983); Heugens & Lander (2009: 74)
	fields with impermeable boundaries	the power of isomorphic forces is higher in fields with strong boundaries than in more permeable fields	Greenwood & Hinings (1996); Heugens & Lander (2009: 74)

Table 1: Technology Institutionalisation Mechanisms (cont.)

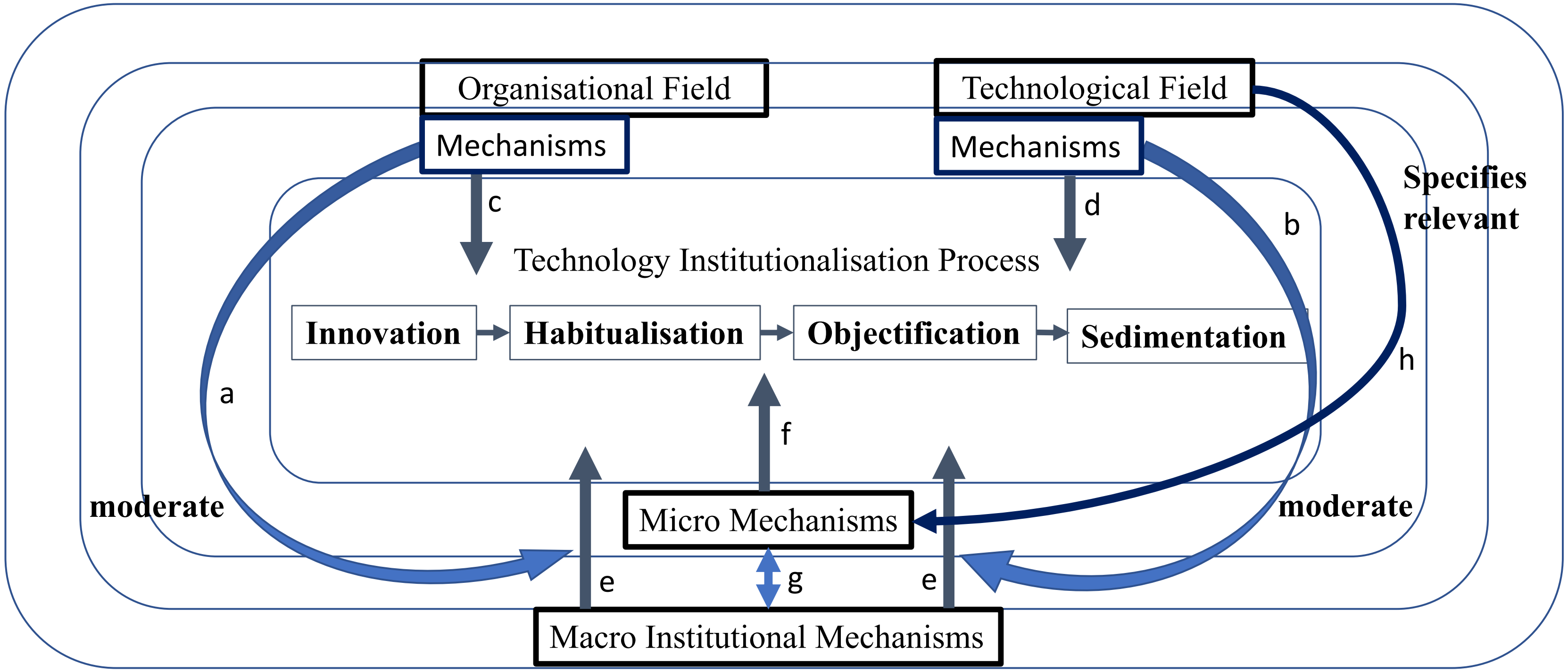
Analytical Level	Mechanism	Description	Reference
	fields with fewer alternative templates	isomorphism is more likely to arise in fields in which there are fewer alternative organising templates to choose from	DiMaggio & Powell (1983); Heugens & Lander (2009: 74)
	previously legitimated templates in other fields	isomorphic forces are stronger for exogenous, previously legitimated templates than for recently established templates that are endogenous to the field. Legitimacy is difficult to create, making the adoption of already legitimated templates attractive.	Heugens & Lander (2009: 74)
Technological Field Moderating Factors			
	technology alternatives	a technological field with relatively few alternatives, experiences stronger isomorphic pressures for technology institutionalisation	Adapted from: Heugens & Lander (2009)
	complexity	technological complexity	Sun & Zhang (2006)
	design	the compatibility among technology components, achieved through a design reflecting a common standard	Garud et al., (2002)
	complementarity	a technology that is compatible with a specific standard in the technological field is more likely to become institutionalised	Makadok & Coff, (2002)
Macro			
	coercive	an organisation pushes a technology through the institutionalisation process to conform to the requirements of a more powerful firm and gain legitimacy	Delmestri, (2007); DiMaggio & Powell, (1983)
	mimetic	adoption and implementation of a technology with the desire of organisations to follow the actions of competitors in the same industry	Scott, 2008).
	normative	technology is adopted to avoid a damage to legitimacy from the perspective of the industry and other institutions	DiMaggio & Powell, (1983); Pishdad et al., (2012)

6. A MODEL OF THE TECHNOLOGY INSTITUTIONALISATION PROCESS

The technology institutionalisation model (Figure 1) illustrates how the institutionalisation process of technologies, as described by Tolbert & Zucker (1996), is influenced by micro, field, and macro mechanisms and their interactions. The model summarises the theoretically and empirically grounded relationships that have been described and discussed above.

At the core of the model is the institutionalisation process as described by Tolbert & Zucker (1996) and applied to the field of technology following Pishdad & Haider (2015). The technology institutionalisation process starts with an innovative technology that goes through a three-stage process consisting of habitualisation, objectification and sedimentation. This process is influenced by macro, organisational/technological field, and micro-level mechanisms which also show interactions among each other. Field-level mechanisms have a direct influence on the technology institutionalisation process [link c and d] but also moderate macro institutional mechanisms (coercive, normative, and mimetic pressures) [link a and b]. It is argued here that mechanisms can be identified that are specific to either the organisational field [link a and c] or technological field [link b and d]. In comparison to the organisational field concept, the technological field has a clearer focus on the technology (design considerations etc.), which is at the centre of the institutionalisation process as described in this study. The technological field also specifies the technological aspects [micro-level mechanisms, link f] that are relevant for the institutionalisation process [link h]. Further, I have described the macro-level institutional pressures [link e] that have a direct influence on the technology institutionalisation process. There is also an interaction between macro and micro mechanisms that influence this process [link g]. Micro mechanisms influence technology institutionalisation directly [link f] but habitualised actions and intentions can also be transformed into macro-level structure (Li, 2017: 4) through link g which then influence the technology institutionalisation process.

Figure 1: The Multi-Level Technology Institutionalisation Model



{coercive, normative, and mimetic pressures}

7. DISCUSSION AND FUTURE RESEARCH DIRECTIONS

This article contributes to research on institutionalisation processes in two ways. First, institutional theory has mainly focused on isomorphic pressures as macro-level mechanisms that influence the institutionalisation process. I, however, have argued that a better understanding of this process requires the incorporation of micro, field-specific, and macro-level factors. A major aim of this research has been to encourage institutionalists to a more active engagement with technology. In this article I have directed attention to the interactions between micro and macro mechanisms as well as field-level influences that both moderate the influence of institutional pressures and influence the institutionalisation process of technology directly. The concept of the technological field is introduced as a complement to organisational fields to emphasise the focus on the technology with its specific mechanisms that contribute to its institutionalisation. This article extends existing research on institutional theory and institutionalisation processes by suggesting a multi-level and multi-field perspective. Particularly, I have argued that a model of technology institutionalisation needs to incorporate micro, field, and macro levels of analysis and treat them as complementary perspectives. I have drawn on the conceptualisation of technology as an institution in its own right to emphasise its independent influence in the institutionalisation process. This conceptualisation has rarely been used in institutional theory also due to the underrepresentation of technology in this stream of research.

The sparse literature on technology institutionalisation has mainly focused on information technology and systems as they represent forms of technology that are omnipresent in organisations. It has to be noted, however, that IT institutionalisation is only a narrow view of technology institutionalisation. This paper, despite referring to information technology as a prime example, aims to develop a more holistic view of technology institutionalisation that can also be applied to other types of technologies. Institutional theorists are therefore encouraged to apply a multi-level perspective to empirically examine the institutionalisation process of other types of technologies.

Further research is needed to empirically test the suggested model and to further specify boundary conditions. Since the generality of mechanisms is limited, more research investigating technology mechanisms is required. A promising avenue for future research would be to further investigate additional mechanisms that influence technology institutionalisation. I emphasised the need for organisational studies and institutionalists in particular to engage more with information technology as a phenomenon with distinct characteristics and an ever-increasing influence on organisations. We need to better understand how information technologies are institutionalised in order to realise the potential unintended consequences from overly relying on taken-for-granted institutions. I therefore encourage future studies examining the risks associated with technology institutionalisation. From a strategic management perspective, a fruitful area of research would be to examine the implications of technology institutionalisation on performance for both the organisation and technological field that adopts the technology.

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