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Three electricity futures: Monitoring the emergence of alternative system architectures

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ABSTRACT

The electricity system is in transition, but whereto? To large-scale global or regional grids or to self-sufficient disconnected prosumers? Although numerous studies have previously dealt with the future of the electricity system, there is a lack of studies that attempt to monitor the development of more complete sets of socio-technical system elements that support alternative futures. This paper addresses this gap by first identifying and characterizing three idealized electricity system futures: 'the Super-grid', 'the Smart-grid' and 'the Off-grid', and then using the characterization to monitor the emergence, accumulation and alignment of socio-technical elements indicating the initial formation of new systems. Besides tracing the ongoing structural build-up at the niche level, we explore how the emerging systems relate to the existing electricity regime, other sectors and discourses. While the final outcome is undecided, the findings indicate that all three of the investigated systems have gained momentum over the last decade, partly relying on growth trends in shared elements such as the rise of renewables and climate change concerns, but also building on different technologies, actor networks, related industries and political and cultural discourses.

1. Introduction

At the turn of the century the electricity sector was strikingly similar in different parts of the world, based on a model of centralised and large-scale power generation (IEA, 2016a). This system is now facing problems related to climate change, local air pollution, nuclear safety, energy security and aging grid infrastructure, and, consequently, undergoes a transformation towards larger reliance on smaller scale power plants based on renewable energy (RE) (Frankfurt School-UNEP Centre/BNEF, 2016). The technical potential of solar and wind power exceeds current and projected energy demand (Sandén, Hammar, & Hedenus, 2014), and economic competitiveness of these technologies is being reached in an increasing number of regions around the world. In 2015, the global annual installation of solar and wind surpassed 100 GW despite a significant decline in fossil fuel prices (GWEC, 2017; IEA, 2016b). In addition, rapid innovation in technologies for balancing electricity supply and demand across time and space, such as, high voltage cables, energy storage (incl. electric vehicles) and information and communications technology (ICT), is facilitating a transition to an electricity system solely based on renewables. There are, however, several radically different electricity system architectures, that all could satisfy the criterion of hundred per cent renewables, but these would entail different benefits and drawbacks and affect societal actors in various ways. Hence, there is a value in monitoring the development to better understand what is going on and to gain some foresight. While socio-technical change is highly non-linear and to some degree unpredictable, it is not without logic and the process can be studied.

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Previous work on electricity system futures has either focused on techno-economic assessment of different system configurations (Battaglini, Lilliestam, Haas, & Patt, 2009; Blarke & Jenkins, 2013; Funcke & Bauknecht, 2016; Meeuwsen, Myrzik, Verbong, Kling, & Blom, 2008), analysis of existing supporting organizations (Lilliestam & Hanger, 2016), or construction of narrative scenarios (Foxon, 2013; Foxon, Hammond, Pearson, Burgess, & Hargreaves, 2009; Verbong & Geels, 2010). There are also numerous reports on the development of singular components. There is, however, a lack of studies that monitor the development of more complete sets of socio-technical system elements and put these in relation to clearly distinguishable alternative futures and transformation pathways.

Such monitoring can take as starting point a conceptualisation of the electricity system as a socio-technical system in transition (Geels, 2004), where different alternative solutions emerge, compete and coevolve (Sandén & Hillman, 2011). A broad stream of literature on socio-technical systems and technological change describes such path-selection as a process emerging out of accumulation and alignment of heterogeneous structural components, such as actor constellations, technical artefacts and institutions (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Geels, 2004; Hughes, 1987b; Kemp, Schot, & Hoogma, 1998; Rip & Kemp, 1998). Some of these components may be closely linked to, and build upon, the dominant electricity 'regime', as well as other established systems and sectors; while others develop in more isolated niches (Raven, 2007).

The aim of this paper is to systematically monitor key structural system components that support different scenarios of future electricity system change. From this we derive four research questions:

- What alternative future electricity system scenarios can be identified?
- What structural components characterise these scenarios?
- Which of these structural components are emerging and accumulating at present?
- How are the alternative scenarios and their emerging components linked to, or decoupled from, the current electricity regime; and to what extent are they borrowing strength from other sectors and trends?

We address the first two questions by deriving three idealised exploratory scenarios (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006) from a literature review and identifying their overall characteristics and signifying structural components. To address the third question, we use an extensive web-based search to monitor the accumulation of technology, actors and networks, and institutions. Based on these findings, the fourth question is elaborated on in a discussion on socio-technical overlaps (Sandén & Hillman, 2011).

2. Theory and method

In the following, we review key concepts from the socio-technical systems literature that provide the theoretical base for exploration of electricity systems in transition, and provide a methodological framework for monitoring emergence of alternative system architectures, including: identification of ideal system types; monitoring accumulation of heterogeneous components that may form building blocks of these systems; and analysing overlaps with other systems. Thereafter, methodological choices on data sources and system boundaries are reported.

2.1. Socio-technical systems and transitions

The dominant model for electricity supply, based on large-scale centralised installations and extensive grid infrastructure, has been described as a large technical (or socio-technical) system (LTS) (Hughes, 1987a; Loorbach, Frantzeskaki, & Thissen, 2010; Markard, 2011). An LTS consists of numerous heterogeneous components, including physical artefacts as well as social, economic, institutional and organizational structures (Geels, 2002; Hughes, 1987a; Loorbach et al., 2010; Verbong & Geels, 2010). The number and high degree of alignment between components creates inertia and "lock-in" (Unruh, 2000). However, history teaches that also such locked-in systems can and will be replaced, a phenomenon that has been termed 'technological transition' (Geels, 2002). Previous research has identified multiple processes driving such change. Transitions can be triggered by new discoveries that offer new opportunities or by efforts to address major problems within the old system, or, more likely, by both processes in combination (Geels, 2002; Geels & Schot, 2007; Sandén & Jonasson, 2005). The Multi-Level Perspective (MLP) describes transitions from one established socio-technical system to another as unfolding from interaction between processes at three systemic 'levels' (Geels, 2004, 2011; Rip & Kemp, 1998): first, the regime level, the essence of the large technological system, where a well-established set of institutions is shared by a large number of actors aligned in efficient value chains utilising mature technologies to deliver a certain good or service; second, the landscape level, where broad societal trends unfold that may put pressure on the regime and thus open up windows of opportunity for novelties; and third, the niche level, where new configurations emerge, grow and gain momentum. Phrased in the language of the MLP model, this paper studies structural build-up at the niche level, which indicates the direction of the ongoing transition, i.e. the development of *alternative socio-technical systems* and their components.

2.2. Identifying alternative future systems

To be able to trace the build-up of alternative systems one needs to have an idea of what to look for. In the early days of a transition, however, it is not a trivial task to discern what potential future systems that may eventually emerge. One strategy is to pick alternatives that are frequently discussed, and that some actors consider to be 'realistic'. However, since what is considered 'realistic' is often based on myopic worldviews very much coloured by present day systems, this might lead to a too narrow scope. To broaden the search, scenario methodology can be of help.

Depending on purpose, different types of scenario methodology is applied (Börjeson et al., 2006). One distinction can be made between forecasting and backcasting. Backcasting typically has a normative starting point, a system that someone would like to see materialise in the future. The analysis then identifies scenarios leading to that system. Here, we have no such normative starting point. Instead, the overarching ambition is to take one step towards *forecasting* the development of the electricity system. Forecasting typically builds on trend analysis, possibly also on quantitative modelling of interactions between several trends and time-independent constraints. However, since technological transitions are inherently messy and involve long-term processes where heterogeneous elements interact in a non-linear way, it is not immediately clear which trends and constraints one should look for, how to group them in a meaningful way and how to model interactions. Forecasting in any precise way is impossible.

However, one can draw a map of potential futures to create a ‘design space’ (Stankiewicz, 2000). Like every space, the design space has dimensions, and every conceivable system should be possible to describe in terms of these dimensions. Instead of deciding, a priori, what are realistic futures within this space, the analyst can first look at the extreme positions. The development from the current state towards one of these extreme positions forms an idealised scenario. Such idealised explorative scenarios take as a starting point, neither what is desirable, as in backcasting, nor what is likely, but what is theoretically possible (Börjeson et al., 2006). The key *socio-technical components* of these truly alternative scenarios and endpoint systems can then be the focus of monitoring and trend analysis, which in turn is used to determine which scenarios that are starting to materialise.

2.3. Tracing structural build-up by monitoring system components

At one level, the idealised electricity systems can be described by a set of technical artefacts and their relations. However, these need to be accompanied by constellations of actors and institutions that together with the technical components form a socio-technical system. While using slightly different concepts and delineations, various strands of the socio-technical and innovation systems literature seem to agree on a limited number of distinguishable component categories of such systems (Bergek, Jacobsson, Carlsson, et al., 2008; Geels, 2004; Hughes, 1987b; Kemp et al., 1998; Rip & Kemp, 1998; Sandén & Hillman, 2011; Wieczorek & Hekkert, 2012). Here, we structure the empirical data following a categorisation from the technological innovation system (TIS) framework (Bergek, Jacobsson, & Sandén, 2008), an approach that has dealt in detail with the emergence and growth of novel socio-technical systems. Hence, we primarily distinguish between technology, actors and networks, and institutions.

Technology here refers to physical artefacts that make use of natural phenomena to produce services (Arthur, 2009), and to descriptions of the same processes, commonly referred to as technical knowledge (Bergek, Jacobsson, & Sandén, 2008; Sandén & Hillman, 2011). *Actors and networks* refers to an organizational dimension populated by people (Sandén & Hillman, 2011), where ‘actors’ refers to individuals or groups of individuals that are hierarchically linked in organizations, and ‘networks’ to more loosely linked groups of actors. ‘Organizations’ includes not only firms but also knowledge institutes, industry associations, and governmental or non-governmental organizations. *Institutions* refers to rules that regulate interaction, mainly between actors, but sometimes also between artefacts (Bergek, Jacobsson, Carlsson, et al., 2008; Bergek, Jacobsson, & Sandén, 2008). The category includes regulative, normative and cognitive institutions (Palthe, 2014; Scott, 2001). Regulative and normative institutions include hard regulations controlled by the juridical systems and norms and attitudes towards what is desirable. The cognitive institutions i.e. beliefs and expectations about what is reasonable, or “true” and taken for granted, are as important. Technologies do not pre-exist by themselves but are created through beliefs and expectations about how the world works and will develop. Beliefs and expectations shape the perceived potential and future materialisation of different technologies (Borup, Brown, Konrad, & Van Lente, 2006; Van Lente, 2012; Van Lente et al., 2013).

Some of the required components need to be developed afresh specifically for the targeted system, while others can be ‘borrowed’ from other systems due to *socio-technical overlaps*.

2.4. Socio-technical overlaps, niche accumulation and hybridization

As observed already by Schumpeter (1934), new systems are never independent of old structures and innovation is essentially a process where older and newer elements are combined in novel ways. This means that new electricity systems will make use of technology, actors and institutions available in the old electricity regime and/or borrow such elements from other sectors. In other words, a new system may have a larger or smaller socio-technical overlap with the regime and other industries (Sandén & Hillman, 2011). Novel systems may also share system components with other emerging systems enabling development not only through competition but also through complementarities (Markard & Hoffmann, 2016), leading to parasitic or symbiotic relations (Sandén & Hillman, 2011); the development of one piece of technology, actor constellation or legislation may benefit more than one alternative system.

With regards to the relation between niches and regime, Raven (2007) points at two general ways to create spaces for new systems – niche accumulation and hybridization – that differ in their level of overlap with the regime. *Niche accumulation* is the process where novel systems build up internal momentum, i.e. improve technically and gain economic and political strength, by experimentation and deployment in specific separate niches where the novelty has some kind of performance advantage (Kemp et al., 1998), and where new niches are added as the systems develop. In this case the novel system, or ‘technology’, tends to borrow more from other sectors. A case in point is solar PV that initially was related to and benefitted from the electronics and space industries, and which only lately has made an impact on the energy sector. Another is lithium-ion batteries, that have developed through application in, first, consumer electronics and, then, electric vehicles, now making them viable for wider application in the electricity system. In the case of *hybridization* the development, instead, starts closer to the dominant regime by forming hybrid technologies (Geels, 2002) or 'bridging technologies' (Sandén & Hillman, 2011) that partly build on the old and partly on the new system, which then deviates to more radical forms. The use of the old electricity grid itself in new configurations is an example of hybridisation based on a shared component. Another, more speculative, example is electromobility that could develop into a bridging technology by first relying on and supporting the traditional electricity system and its actors, but also, over time, demanding and facilitating its transformation into something quite different.

The identification of overlaps may provide insights into the speed and strength of different accumulation and alignment processes.

2.5. System boundaries

While most things in this world are linked in some way, we need system boundaries to delimit and focus data collection. Here, the unit of analysis is not a single technical component but alternative systems comprising various socio-technical components. We set the socio-technical boundary to include components directly involved in electricity generation, storage and transmission. We acknowledge that reconfiguration of the electricity system will happen in parallel to transformations of other energy supply chains, e.g. biofuels for heating and transportation, but these are outside the scope of our analysis. Since the purpose is to investigate systems based on hundred per cent renewable (not merely climate neutral) energy, development within nuclear energy and carbon capture and storage (CCS) is not monitored, neither is the development within various electricity end use categories (with the exception of electric vehicles that also can function as storage and balancing technology). Since the electricity system cannot be changed overnight, pathways to hundred per cent renewables require phases where nuclear, coal and natural gas power plants play important roles in balancing the system (Göransson, Goop, Odenberger, & Johnsson, 2017; Johnsson, Odenberger, & Göransson, 2014; Qadrdan, Chaudry, Jenkins, Baruah, & Eyre, 2015). The dynamic techno-economic interplay between different power sources in the electricity mix is of relevance for an in-depth analysis of hybridisation in the electricity systems of individual countries or regions. This is, however, outside the scope of the study. The purpose of this paper is to monitor the development of main components of future (endpoint) electricity systems based on 100% renewables, and to discuss a broader set of sociotechnical overlaps with the current electricity system and other sectors.

Furthermore, we set the spatial boundary at the global level. Although many transition studies choose national or regional boundaries, partly for practical reasons, we believe that, in this case, the national scale limits us from capturing key trends. Transitions of this scale in a globalised world economy are partly shaped by supra-national actors such as multi- and transnational organisations (Coenen, Benneworth, & Truffer, 2012; Hansen & Coenen, 2015), and maybe even more so by the aggregated impact of phenomena originating in different countries and spreading across the world, combining in new ways.

While, arguably, many roots of current trends stretch far back in history, for practical reasons, the temporal boundary of data monitoring is set to 2000–2016.

2.6. Data

Data were collected from a range of secondary sources. First, we reviewed the existing academic literature to identify three idealised system types that could be positioned at extreme points in a two-dimensional design space. In the second step, we used academic literature to identify key socio-technical components of the alternative systems. The findings from the literature review were coupled with data collected from websites, reports, newspaper articles and online datasets to monitor potential growth trends among these components. The data is limited to sources available in English. While limiting the depth of analysis, our use of only secondary data sources enabled scanning of a very broad empirical field within a limited timeframe.

3. Idealised future electricity systems

In this section, we first identify three alternative idealised future electricity system architectures and then trace their evolution in terms of emerging and accumulating system components.

3.1. Three scenarios in one design space

Based on existing literature, we found *the level and type of interconnectedness* to be a decisive characteristic in descriptions of different future renewable electricity systems. In principle, one can distinguish between systems of dependent, interdependent and independent electricity consumers (Fig. 1). These idealised network models correspond relatively well to three articulated visions: the 'Super-grid', the 'Smart-grid' and the 'Off-grid'.

In their extreme forms, these idealised systems are positioned in three different corners of a *design space* that can be described by two variables, the number of production units (P) and the number of grids (G) in the world, and how they relate to an assumed constant number of consumers (N) (Fig. 2). The Supergrid (A) then represents a step from the current system (X) towards the extreme case where there is only one centralised production unit ($P = 1$) in one global grid ($G = 1$). All consumers are dependent on this one production unit. The extreme version of the Smart-grid configuration (B) also shows maximum global connectedness ($G = 1$), but has as many production units as consumption units ($P = N$). Every consumer is also a producer, i.e. a prosumer, and they are all interdependent. Finally, the endpoint of the extreme Off-grid scenario (C) is a completely disconnected system having as many 'grids' as

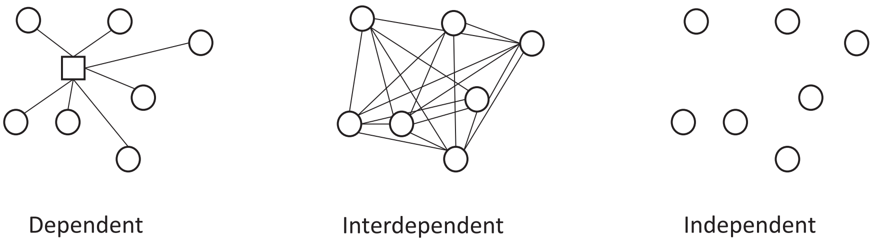

Fig. 1. Different system organizations of electricity consumers and producers representing the 'Super-grid', the 'Smart-grid' and the 'Off-grid' scenarios.

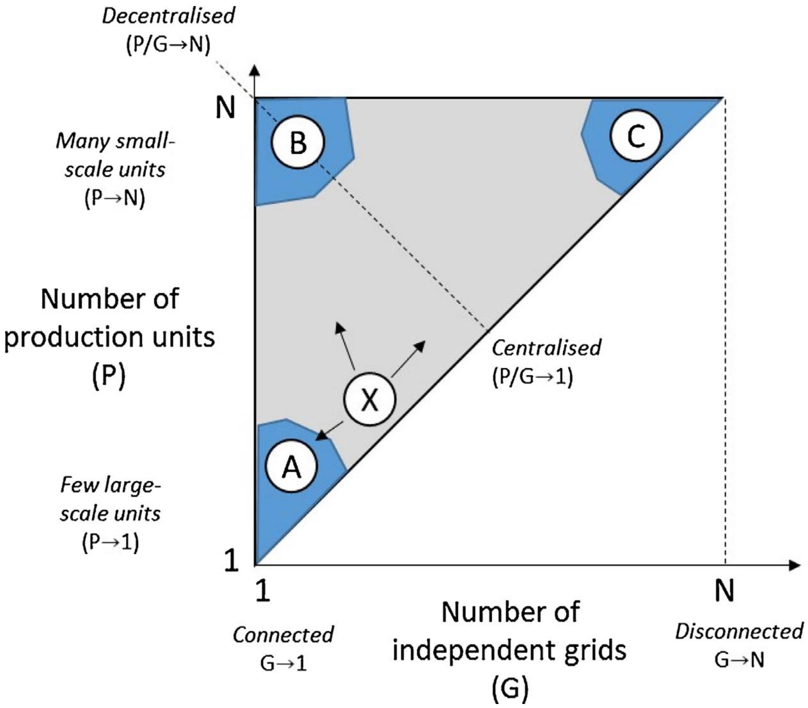

Fig. 2. Three scenarios in one design space. The number of independent grids (G) (x-axis), and the number of electricity production units (P) (y-axis), can vary between 1 and the number of consumption units (N). The current electricity system (X) may develop towards a 'Super-grid' (A), a 'Smart-grid' (B) or an 'Off-grid' system (C).

production and consumption units (G = P = N). Every consumer is independent. One can then note that the Super-grid and the Off-grid scenarios have one attribute in common: centrality, i.e. each grid is hierarchically organised with one production unit per grid (P/G = 1), allowing for top-down control in each grid. The extreme Smart-grid on the other hand is the 'ideal market' with extremely decentralised production (P/G = N), no hierarchy and no top-down control.

If we assume that the number of production units does not exceed the number of consumption units, any system configuration can be positioned within the design space illustrated by the grey triangle in Fig. 2.

To bring clarity to the analysis we select idealised systems that are positioned quite close to the extreme corners as a starting point, instead of striving to identify some arbitrary 'realistic' scenarios (that are bound to be strongly coloured by present day dominant discourses). This also makes it easier to discuss various hybrid and middle-ground system configurations at a later stage. In the following, we refer to our idealised scenarios (and the visionary concept or idea) with capital letter, e.g. the Super-grid. The literature is inconsistent in spelling, so we use organizational and project names as they appear in the literature, e.g. the "European Supergrid".

As illustrated in Fig. 3, a bibliometric analysis indicates a rapidly growing interest, in relative terms, in all three scenarios. The next step is to monitor the emergence of key socio-technical components that enable, or are required for, realization of the three alternatives. An overview of main socio-technical components of the three scenarios, detailed in the following sections, are provided in Table 1.

3.2. The Super-grid scenario

One articulated vision is a system characterised by highly centralised renewable electricity production and large-scale transmission over long distances, spanning across continents or even the entire globe (Battaglini et al., 2009; Funcke & Bauknecht, 2016).

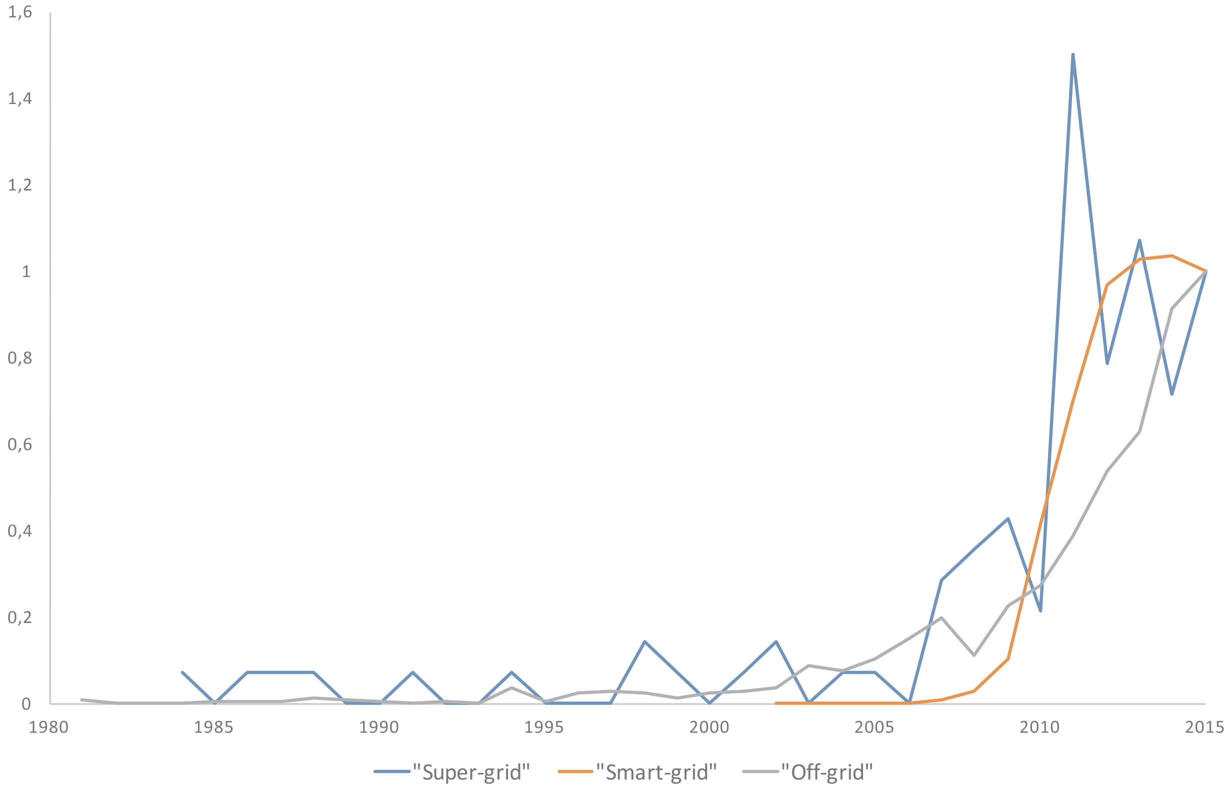

Fig. 3. Relative growth of interest in three emerging systems. Number of academic articles in the database Scopus that explicitly refer the three system architectures: Super-grid, Smart-grid and Off-grid. All numbers are scaled to the publication rate in 2015. See also Fig. 6 for absolute numbers. Search terms: 'Super-grid', 'Smart-grid', 'Off-grid'.
Source: scopus.com

Table 1
Socio-technical components of the three idealised scenarios.

	Super-grid	Smart-grid	Off-grid
Key technical components	Large-scale RE technology parks or plants	Small-scale RE technology	Small-scale RE technology
	HVDC cables	Flexible AC transmission systems	Small-scale storage
	Voltage source converters	ICT, smart metering, smart sensors	Microgrids
	Large-scale storage	Small-scale storage	
		Electric vehicles	
Main actors	National governments & international organizations	Regional & national governments	Prosumers
	Transmission System Operators	Distribution System Operators	Private device developers and maintenance providers
	Large, often state-owned vertically integrated utility companies	Incumbent firms and new entrants from other sectors (ICT, automotive sector)	
	Incumbent power system companies	Prosumers	
Supporting institutions	Collaboration and harmonization between governmental, regional, international projects	Collaboration along the new supply chain	Mistrust in the existing electricity market actors
	Multilateral agreements	Standardization	Norms related to independence, self-sufficiency or direct contribution to climate neutrality
	Tenders	Feed-in-tariffs	Innovative practices for financing (microfinance, pay-as-you-go)
	Vision statements, roadmaps	Expectations translated into demonstration projects	

The rationale behind such a ‘Super-grid’ is to make efficient use of unevenly distributed renewable energy resources, connect them to load centres, and handle large-scale penetration of variable energy sources, while avoiding the need for storage or demand flexibility (Blarke & Jenkins, 2013; Liu, 2015). It requires close cooperation between central governments and an exclusive number of manufacturers, utilities and transmission system operators (TSOs) (Foxon, 2013). The Super-grid scenario resembles the ‘greening of the centralised production’ scenario, proposed by Verbong and Geels (2010), as the incumbent actors of the dominant electricity sector are assumed to keep their positions, while electricity consumers remain a passive part of the system.

3.2.1. Technology

The envisioned electricity system of the Super-grid is based on large power plants, typically power parks at the multi GW scale of on-shore wind in desolated areas, off-shore wind at sea, and solar photovoltaics (PV) and concentrated solar thermal power (CSP) around the equator, combined with large-scale installations of tidal and wave power, biomass and geothermal energy where available (Battaglini et al., 2009; Foxon, 2013; Meeuwsen et al., 2008). Generation is connected to load centres with long distance extra high (EHV) and high voltage cables (HV).

Technology seems not to be a show-stopper for turning the global Super-grid into reality (MacLeod et al., 2015). In fact, most of the technical components required are relatively mature and some already exist as parts of the current electricity system. In addition, knowledge production in key technologies has accelerated over the last decade, as illustrated in Fig. 4. HVDC technology is of particular interest since it enables very long-distance transmission on land and ocean floors. According to MacLeod et al. (2015), 2013 saw a breakthrough in HVDC technology, with the introduction of the voltage source converter (VSC) that allows for 50% higher voltage level and the HVDC circuit breaker that is crucial for reliable operation of an interconnected HVDC infrastructure.

While a Super-grid can reduce the need for storage, as excess of power at one place can be transferred to other places, the grid also enables hydropower stations to be used as centralised storage. Such storage potential already exists in about 40 countries (Williams, 2016), possibly best exemplified with the endeavour to turn Norway’s hydropower plants into Europe’s battery (Fairley, 2014).

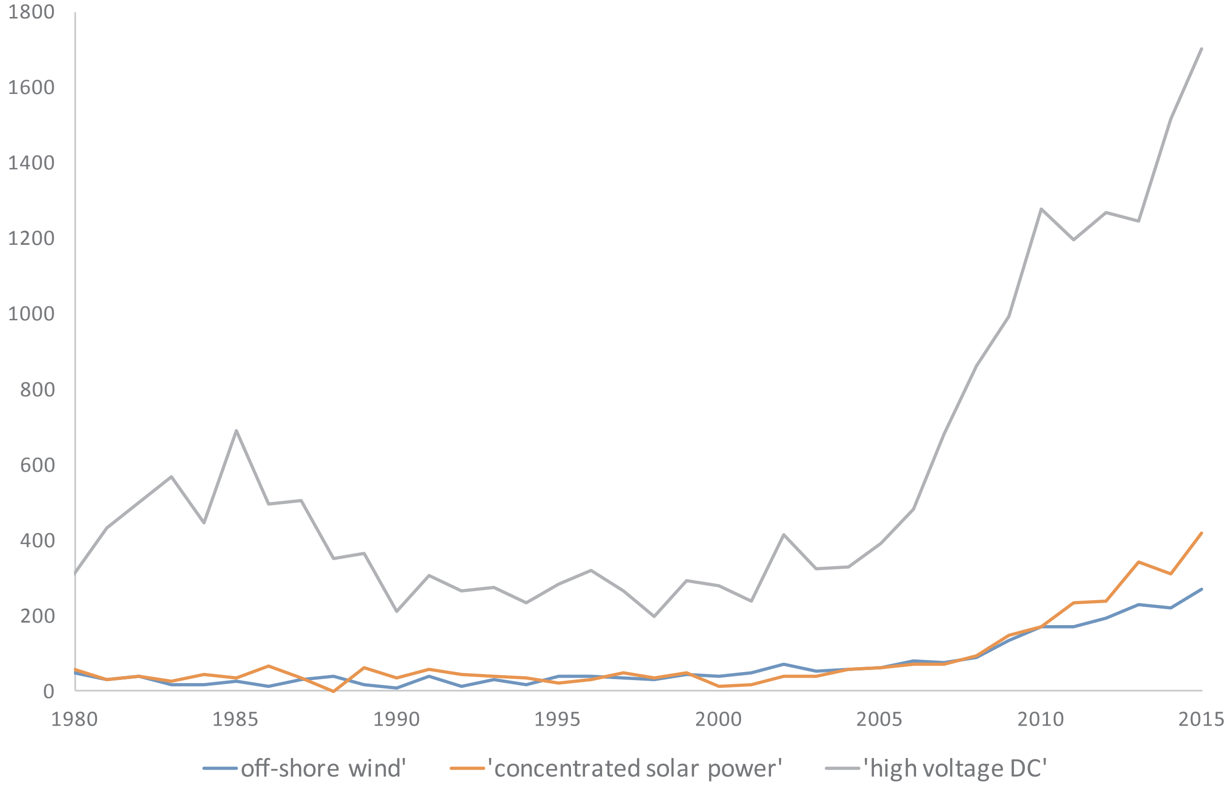

Fig. 4. Knowledge creation related to three characteristic technical components of the Super-grid system (values are deflated by scaling annual values to total annual number of publications in the database). Search terms: ‘off-shore wind’, ‘concentrated solar power’, ’high voltage DC’.
Source: scopus.com

3.2.2. Actors and networks

A Super-grid interconnecting all the corners of the world today only exists as an ambitious idea. The planning and implementation of cross-national grids has, so far, been based on 'the government logic' with a strong political character, according to which national government actors together with a few large private stakeholders coordinate expansion to achieve energy policy goals (Chatzivasileiadis, Ernst, & Andersson, 2013; Verbong & Geels, 2010). The construction of Super-grid infrastructure is currently in the hands of a few leading incumbent power system companies such as the ABB, Siemens and GE Grid Solutions.

A significant number of actors and networks advocating the Super-grid can be found in EU and surrounding regions. In 2008, the European Commission called for the construction of regional transmission grids that could eventually be linked into a pan-European Super-grid and supply Europe with renewable power generated from the Mediterranean region to the North Sea[1] (Gellings, 2015). The European Network of Transmission System Operators (TSOs) for Electricity (ENTSO-E), an association of 42 TSOs, from 35 countries, has been given the responsibility to develop a roadmap towards a pan-European power system by 2050, known as e-Highway2050. Since 2012, the industry association Friends of the Supergrid (FOSG) has published annual reports on the roadmap (FOSG, 2016). FOSG represents the entire supply chain required for construction of a Super-grid, comprising of TSOs, experts from cable manufacturers, project developers, consultants and logistics companies (MacLeod et al., 2015).

Dominant actors promoting the Super-grid in the wider European region is the Desertec Foundation and the Desertec Industrial Initiative (Dii), both founded in 2009. Desertec Foundation was formed as a non-profit network of scientists, politicians and economists from around the Mediterranean region with a plan to use HVDC to power Europe by Saharan large-scale CSP. Dii was established as an 'international' consortium of companies with the target of converting the Desertec concept into a profitable business project (Hamouchene, 2015). Dii brings together firms of mainly German origin such as E.ON, Munich Re, Siemens and Deutsche Bank, but cooperates also with Middle East and North African countries, for instance within the Medgrid project (SETIS, 2014).

Inspired by the Desertec concept, an Asian version known as the Gobitec Initiative was proposed in September 2009 by academics in Northeast Asia. The Gobitec Initiative triggered an interest in constructing an Asian Super Grid, which would connect grids of China, Japan, Korea, Mongolia and possibly also Russia (more speculatively also Taiwan, Thailand, the Philippines, and India) and transmit wind and solar electricity from remote areas to load centres. The Asian Super Grid was proposed by Son Masayoshi, CEO of Japan's Softbank, in 2012 after the Fukushima disaster. Later the same year, the first agreement was announced with a Mongolian company, Newcom, on developing a giant wind farm in the Gobi desert that would be connected to the Super-grid (Mathews, 2012). In 2016, the world's largest electricity utility company, the Chinese State Grid, officially joined (Colthorpe, 2016; Minter, 2016). China has recently become the world leader in the development and deployment of HVDC technologies, which shows in the significant growth of kilometres of HVDC in Asia over the last fifteen years (Fig. 5). The Chairman of the Chinese State Grid, Liu Zhenya, publicly called himself a supporter of the Super-grid as it will "create a community of common destiny for all mankind with blue skies and green land", and the Chinese president Xi Jinping proposed an initiative on establishing a Global Energy Interconnection (GEI) to meet global power demand and green alternatives (GEIDCO, 2017; Minter, 2016).

In contrast, in the USA a historical heritage of balkanised grid infrastructure with multiple tiny grids and ineffective regulatory structure has hindered upgrades of the U.S. transmission network and the construction of a North American Super-grid (Kraemer, 2009). The only big project in this direction is known as 'Tres Amigas', proposed in 2009 with the aim of connecting three separate grids: the Eastern Interconnection, the Western Interconnection, and the Texas Interconnection (Kraemer, 2009). In 2015, however, the billion-dollar plan to connect the three grids had failed to meet its milestones after losing a key partner (St.John, 2015). In other parts of the world, such as South America, Australia and Oceania, or Sub-Saharan Africa, few or no actors promote projects aiming at building a Super-grid.

3.2.3. Institutions

The real challenges for turning the global Super-grid into reality are not technical but political and social. According to Gregor Czich, a German Super-grid advocate, if a regulatory framework for the intercontinental grid were established today, our current technical abilities would allow us to build the Super-grid within twenty years (Dauncey, 2009). However, large-scale infrastructural projects across national boundaries is hindered by a low level of institutional alignment (Shuta et al., 2014). A necessary first step towards the required coordination is a shared vision of, and belief in, the Super-grid as the electricity system of the future. Vision statements and roadmaps as well as expectations forming around pilot projects are thus representing the first (cognitive) institutional building blocks of the Super-grid in Europe and Asia (Borup et al., 2006; Van Lente, 2012).

In Europe, FOSG articulates the expectation of the Super-grid as the only means to achieve a 90% decarbonised electricity system in Europe by 2050, as well as an enabler of secure, reliable and cost-effective electricity (FOSG, 2014). Although no legal frameworks or regulations are in place at this point, efforts are made, especially within the EU, to encourage collaboration and harmonization between various projects.

The vision of the Asian Super Grid is backed up by high expectations that it will bring job creation, poverty alleviation and reduction of carbon dioxide emissions (Shuta et al., 2014). To meet these expectations, the Asian Super Grid Initiative proposed the Energy Charter Treaty (ECT), a legal framework for long-term cooperation between countries that are producing, consuming and transmitting energy across the grid. ECT is an inclusive multilateral agreement that provides a comprehensive set of rules covering the entire energy chain from production and generation to the terms under which electricity can be traded and transmitted across

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[1] Projects funded by the European Union: Better Project, E-Highway2050, GridTech Project, Market4RES, MEDOW, NSCOGI, The North Sea transnational grid, The North Sea Grid (FOSG, 2016; Gellings, 2015)

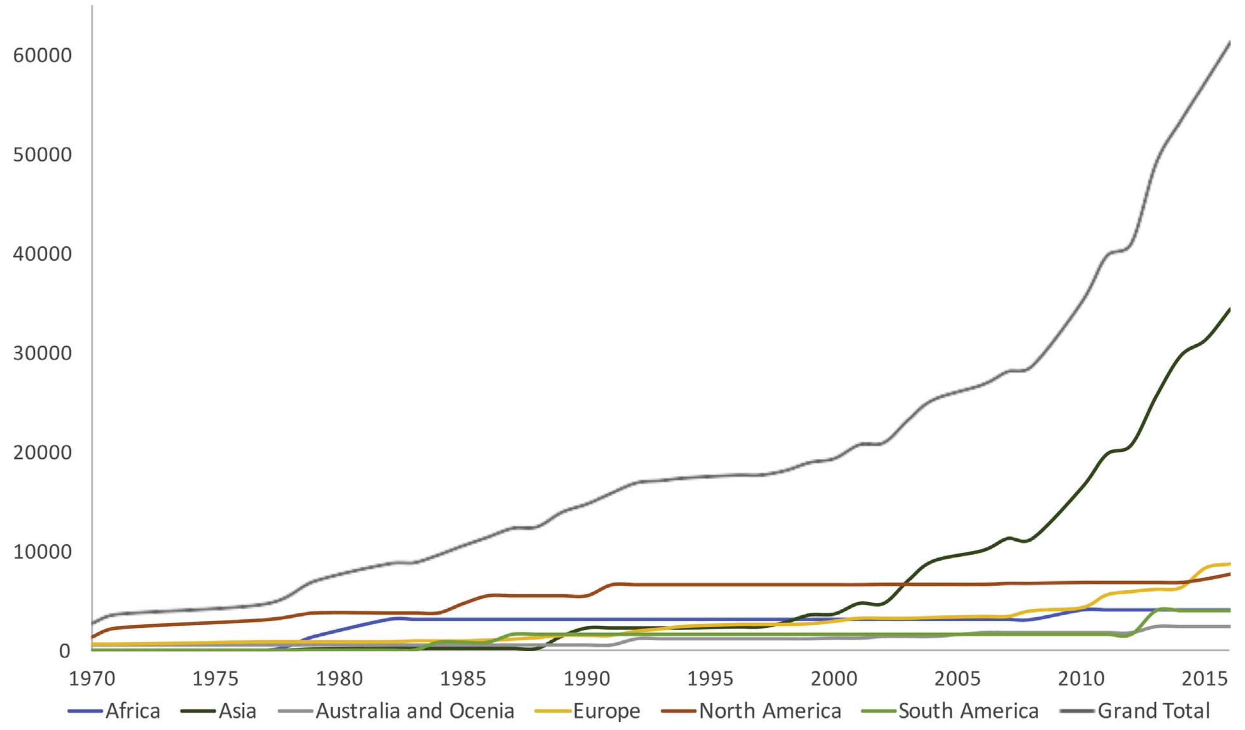

Fig. 5. Number of kilometres of HVDC worldwide (cumulative numbers). (https://en.wikipedia.org/wiki/List_of_HVDC_projects).
Source: wikipedia.org

different national jurisdictions and markets. So far, 52 countries plus the EU and the European Atomic Energy Community have signed the treaty, which serves as a uniting framework for political and legal aspects related to the Asian Super Grid Initiative (Shuta et al., 2014).

Besides these visions and early attempts of grid regulation, we also find that market support of renewables has shifted from investment support and feed-in tariffs (FiTs) towards call for tenders for utility-scale renewable energy projects, which tends to support the development of centralised renewable electricity production. In the case of solar power, the shift from feed-in tariffs to tenders began in 2015 and is expected to continue over the next couple of years (PVPS, 2016).

3.3. The Smart-grid scenario

Another option for the future is a system based on decentralised interconnected electricity production, which we here refer to as the Smart-grid. Although the concept of the Smart-grid can be interpreted in different ways, we understand it as an interconnected bidirectional electric and communication network of ‘prosumers’. Such a system is enabled by the small-scale modular character of many renewable energy technologies (Battaglini et al., 2009). Furthermore, ICT plays a major role in increasing efficiency, reliability and security of the Smart-grid (Blarke & Jenkins, 2013; Hertzog, 2010). Such ‘smart’ technologies enable a system with a flat hierarchy in which everyone has the chance to actively participate in a highly competitive electricity market (Foxon, 2013).

3.3.1. Technical components

From a technical perspective and in comparison with today’s system, the average size of production units and the voltage level decreases and the electricity is delivered over shorter distances (Foxon, 2013). Importantly, a Smart-grid system is comprised of not only electricity networks and renewable electricity generation technology but also of interfaces using various innovative communication, metering and storage technologies. Many of these technologies are already considered mature in both their development and application, while others require further development and demonstration (OECD/IEA, 2011). Fig. 6 shows that the scholarly interest in the concept of the Smart-grid has been notably higher than in the other two system configurations over the last ten years. Looking at some of the individual technical components in a Smart-grid, we can also observe increased research activities (Fig. 7). Technical components typically contributing to a Smart-grid are listed in Table 2.

A key component is the flexible AC transmission system (FACTS), i.e. flexible power electronics that reduce energy losses by enabling real time reconfiguration of power flows. FACTS allows system managers to send more power through the cable, for example at times of peak hours when solar panels generate higher volumes of electricity than usual (Fairley, 2010). ICT in general enables real-time power control and two-way exchange of information between stakeholders (OECD/IEA, 2011). The two-directional flow of information is enabled by Advanced Metering Infrastructure (AMI) technologies, which provide prosumers and local utilities with

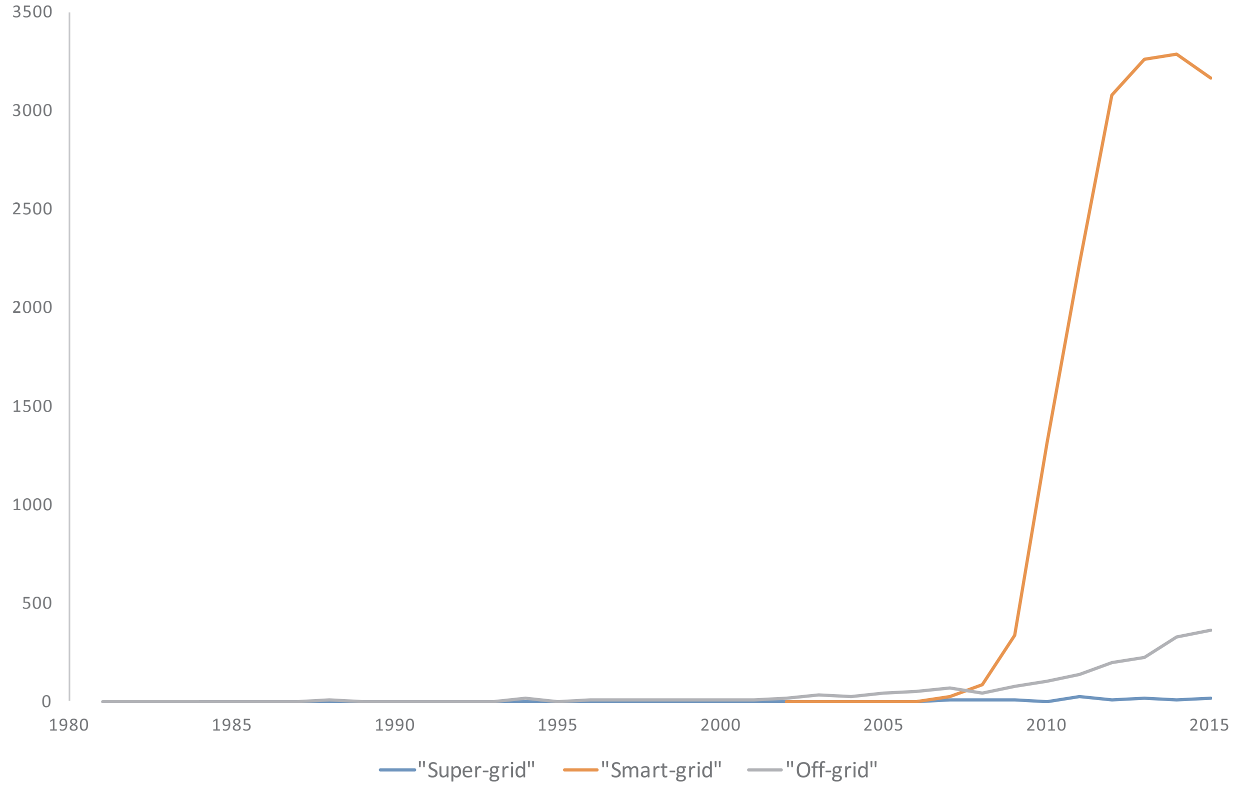

Fig. 6. Number of articles, in absolute terms, related to the three scenarios (compare relative numbers in Fig. 3).
Source: scopus.com

time resolved data on prices and electricity production and consumption (OECD/IEA, 2011). Also other, currently less well-developed, artefacts could solve issues of control in the future smart grid; battery technologies and technologies for distribution grid management and customer-side management are increasingly affordable and accessible (OECD/IEA, 2011). In addition, electric vehicles play an increasingly important role as a flexible balancing technology via the vehicle-to-grid (V2G) concept, in which EV and the grid exchange electricity. Existing research has shown that most vehicles are parked almost 95% of the time. These vehicles could be connected to the grid and deliver stored energy required in case of need to balance local electricity supply. In fact, many assume that since available stationary storage technologies are still expensive, EV batteries can act as dynamic storage devices and support the integration of variable RE technologies into the grid (Mwasilu, Justo, Kim, Do, & Jung, 2014)

One advanced vision of the Smart-grid could be termed the "internet of electricity" (Mazza, 2002), where anyone would be able to upload and download electrical energy packages at any time (Meeuwsen et al., 2008), also known as Peer-to-Peer electricity trading (Murkin, Chitchyan, & Byrne, 2016; Zhang, Wu, Cheng, Zhou, & Long, 2016). The blockchain technology, applied for instance in the financial sector through cryptocurrencies such as Bitcoin, is increasingly promoted to be the future solution for Peer-to-Peer trading and the 'internet of things' (Dickson, 2016). Blockchain seems to offer an alternative to the dominant monopolised supply and distribution of electricity based on administrative systems. Blockchain is a database that automatically records and keeps track of individual actions within a system and stores the results in a secure online folder available to anyone anywhere. In a future system based on prosumers, such technology could enable a quicker and more decentralised transaction system (Hirtenstein & Zha, 2016).

3.3.2. Actors and networks

A global network of actors promoting the Smart-grid is the International Smart Grid Action Network (ISGAN) established in 2010 by the Clean Energy Ministerial (CEM), a regular convention of energy and environment ministers from 23 countries and the EU. The USA initiated ISGAN at the Copenhagen climate convention in 2009. It is a knowledge network that serves as a platform for multilateral intergovernmental collaboration and aims to drive the development and deployment of Smart-grid technologies and systems. ISGAN collaborates with various Smart-grid organizations (IEA-ISGAN.org, 2016). One of these is the Global Smart Grid Federation (GSGF) also established in 2010 as a global stakeholder organization comprising public and private organizations involved in Smart-grid development from 15 countries and the EU. Among members of the GSGF we can find the European distribution system operators (EDSO), Smartgrid Ireland, France and Norway, the Israeli, Japanese and Korean Smart Grid Associations, India Smart Grid Forum and Smart Grid Mexico (globalsmartgridfederation.org, 2016).

The European Commission launched six Europe-wide demonstration projects in 2011, Grid4 EU, that brought together European DSOs; utilities such as Vattenfall, Enel and ERDF; manufacturers such as ABB, Cisco and Siemens; and research institutes. An example

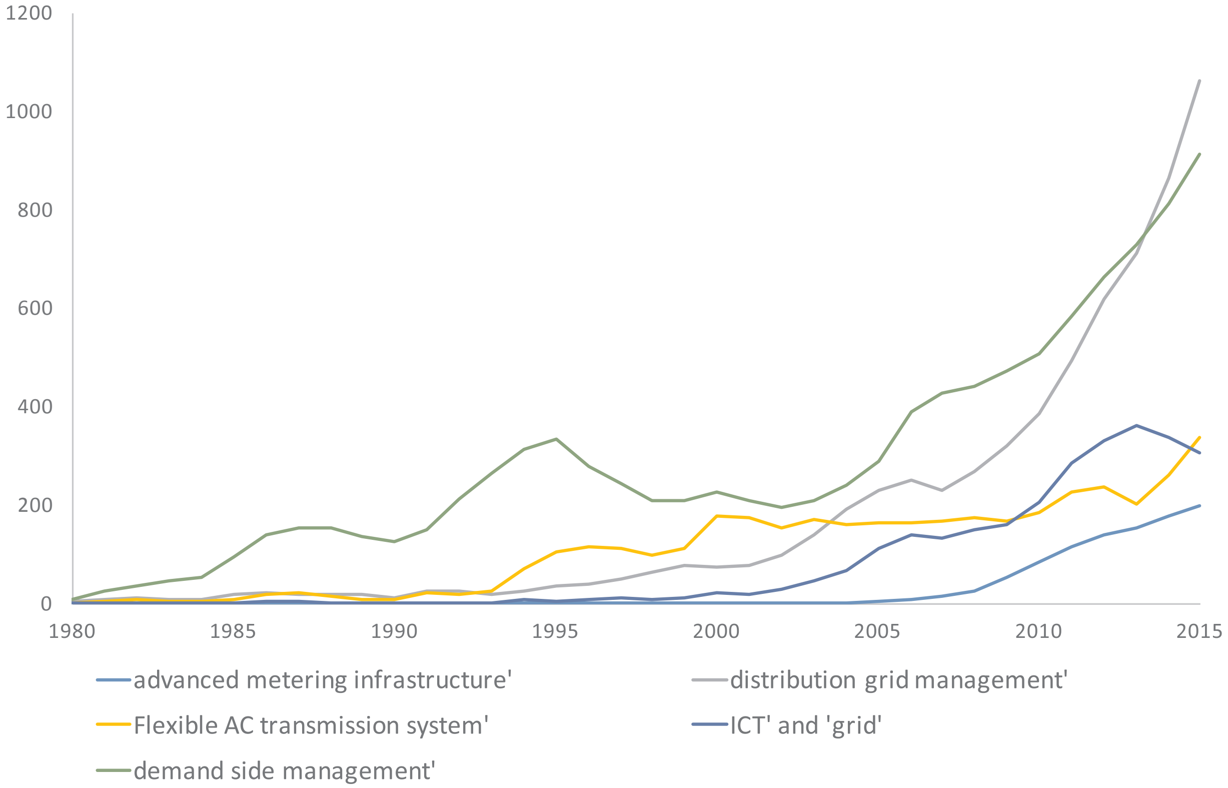

Fig. 7. Knowledge creation related to smart-grid technical components (deflated values). Search terms: 'advanced metering infrastructure', 'distribution grid management', 'Flexible AC transmission system', 'ICT' and 'grid', 'demand-side management'.
Source: scopus.com

Table 2
A selection of smart-grid technical components. Adapted from OECD/IEA (2011, 2015).

Technology area	Technical components	Maturity level
Grid infrastructure	Flexible AC transmission systems FACTS	Mature
ICT integration	Communication equipment Routers, relays, switches, gateway, computers (servers) Customer information system Enterprise resource planning software	Mature
Advanced metering infrastructure (AMI)	Smart meters In-home displays Servers, relays Meter data management systems	Mature
Variable and distributed generation integration	Geographic information and management systems Communication and control technology for generation and storage technology	Developing
Distribution grid management	Remotely controlled distributed generation and storage Transformer sensors, wire and cable sensors Automated re-closers, switches and capacitors Distribution, outage and workforce management systems Geographic information systems Vehicle-to-grid storage and balancing systems	Developing
Customer-side systems	Smart appliances, routers, building automation systems Thermal accumulators, smart thermostat Energy management systems and dashboards Energy applications for smart phone and tablets Blockchain electricity transaction platforms	Developing

is the Nice Smart Solar District at the French Riviera, where voluntary prosumers from residential buildings and commercial local industries had the opportunity to actively manage their electricity consumption (Accenture Consulting, 2015). In total 459 Smart-grid projects from the 28 member states of the EU have been launched between 2002 and 2014. These include all the projects that aim to make the grid intelligent by implementing new technologies and ICT capabilities. Fig. 8 shows the notable increase in the number of new Smart-grid projects between 2003 and 2013 (European Commission, 2014).

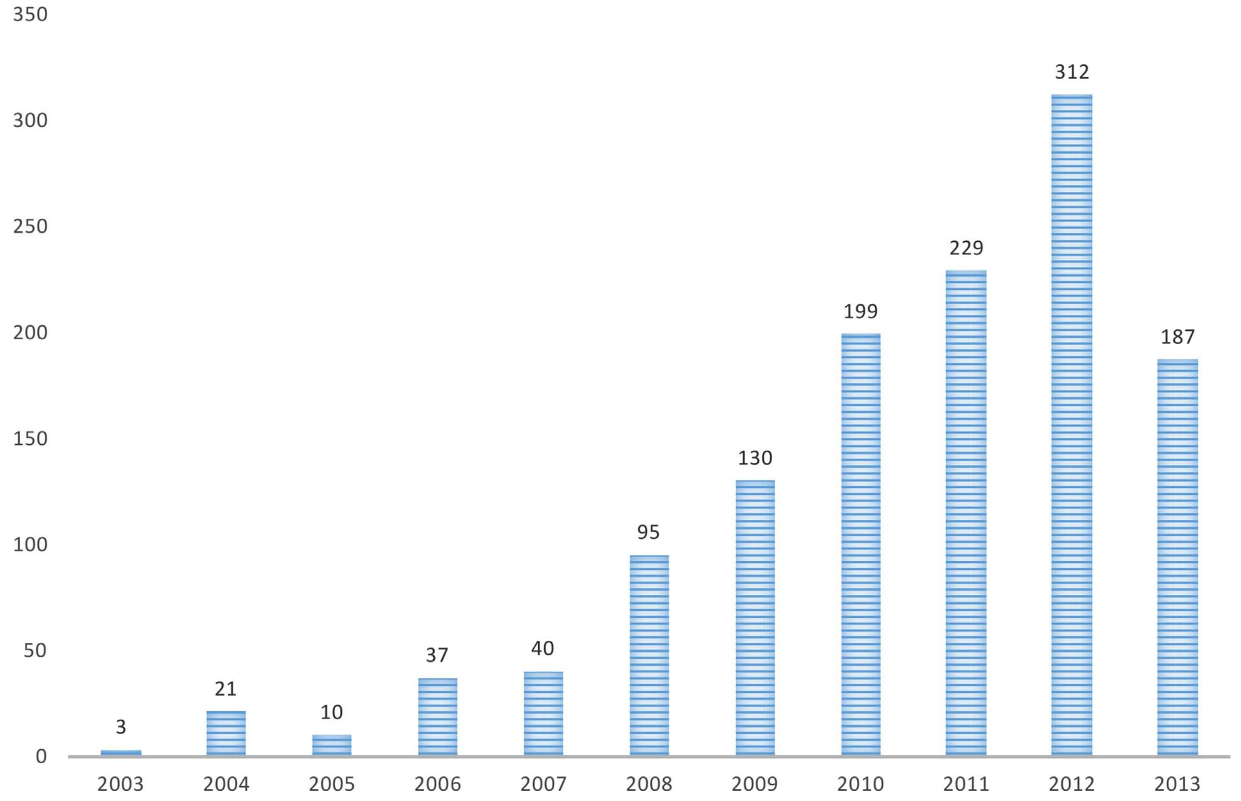

Fig. 8. Annual launch of new Smart-grid projects between 2003 and 2013 in the European Union. Source: http://ses.jrc.ec.europa.eu/smart-grids-observatory.

Furthermore, the Asia-Pacific Economic Cooperation (APEC) launched the Energy Smart Communities Initiative (ESCI) in 2010, proposed by the presidents of US and Japan. ESCI incorporates a knowledge sharing platform that represents a space for collecting and sharing best practices for creating Smart-grid communities (Esci-ksp.org, 2016). After the Fukushima nuclear disaster in 2011, Japan is particularly dedicated to promoting Smart-grids to increase energy efficiency and renewable power generation. The New Energy and Industrial Technology Development Organization (NEDO) has funded several demonstration projects. In 2010, NEDO brought together nine Japanese companies to launch a Japanese-US Smart-Grid demonstration project in Albuquerque, New Mexico. This project is perceived as a good example of the growing international cooperation promoting the Smart-grid (Stuart, 2012). In 2016, NEDO coordinated domestic Smart-grid and international projects in India, Indonesia, China, multiple European countries and the USA.

In North America, dedicated supporting legislation in 2011 resulted in record spending on Smart-grid projects in the USA and Canada. In 2012, the major projects funded by the US Department of Energy included 99 Smart-grid investment grants, 32 Smart-grid demonstration projects and nine renewable and distributed system integration projects (Fulli & Bossart, 2012; Smartgrid.gov, 2016).

Many of the Smart-grid technologies are being developed and supplied by incumbent power system companies, such as ABB and GE producing FACTS, but also incumbents from other sectors such as Siemens testing AMI technologies, Cisco supplying ICT solutions, and Nissan working together with power company Enel to develop ways to use EVs as storage and balancing technologies for Smart-grids (Lambert, 2016). In addition, a growing number of start-up companies are entering the market and receiving increasing capital funding. They offer innovative solutions for Smart-grids, battery technologies and energy efficiency (Hill, 2016). Thus, a more diverse and competitive market is being created around Smart-grid systems compared to the Super-grid.

3.3.3. Institutions

The global community is still in the early stages of creating standards for the technical artefacts and their interoperability in a Smart-grid system. However, despite the lack of universal standards, countries all over the world actively continue Smart-grid related planning and implementation. Given that a Smart-grid system can be built around multiple regional and highly connected systems, the development of standards does not necessarily have to be globally aligned. Rather, alignment needs to take place along the supply-chain, involving various governmental actors, utilities, private vendors and other stakeholders. Their cooperation is crucial for the development of necessary standards (Lundin, 2015). Such collaboration was enabled after the establishment of ISGAN and GSGF in 2010, as platforms that facilitate international discussion related to Smart-grid standardization and development (SAIC, 2011).

In 2016, Smart-grid systems existed in the form of demonstration projects. Expectations attached to these initiatives is what drives the further development of Smart-grids. Although the vision of the smart-grid differs among various actors and networks (Fulli &

Bossart, 2012; SAIC, 2011), the general expectation is to build a grid that can integrate and better utilise distributed small-scale renewables (IEA-ISGAN.org, 2016) and empower the consumer side (ANEC/BEUC, 2010).

3.4. *The Off-grid scenario*

Instead of increased connectedness as in the Smart-grid, the electricity system transition could lead to large-scale grid defection (Zinaman et al., 2015). 'Leaving the grid' and 'living off-grid' have recently become feasible options, mainly due to falling prices of solar cells and batteries.

Hitherto, off-grid systems have mainly been viewed as a solution for poor countries, where people still live without access to well-functioning electricity grids. While off-grid systems are not new and not just a vision, they have been perceived as short-term solutions. However, this understanding is shifting and off-grid solutions are more and more seen as a way to leapfrog the conventional centralised mode and avoid carbon intensive electricity production. Off-grid solutions are increasingly accepted as an essential part of future energy solutions that could provide global access to electricity (Ahlborg & Sjöstedt, 2015; Doig, 1999). More recently, increased attention has been given to the phenomenon of going off-grid also in industrialised countries (Bronski et al., 2014; Khalilpour & Vassallo, 2015).

3.4.1. *Technical components*

Off-grid systems are not connected to large-scale utility grid infrastructure. Instead, they consist of stand-alone systems of power generation and distribution that supply electricity to local communities via a mini or micro-grid, to a single house, or even to individual appliances. Key enabling technologies for off-grid systems are small-scale renewables, such as PV, wind or micro-hydropower plants coupled with a storage technology (Zinaman et al., 2015). Off-grid systems based on small-scale hydropower and diesel generators have a very long history, but the recent cost reduction and availability of solar PV and batteries has given off-grid systems a renaissance. The rapid development of these key enabling technologies is also reflected in scholarly knowledge production (Fig. 9).

At the household level, the use of Solar Home Systems (SHS) in developing economies is not new but increasingly affordable, and SHS are nowadays seen as a leapfrogging technology for communities without access to the national utility grid. Also, SHS are used in

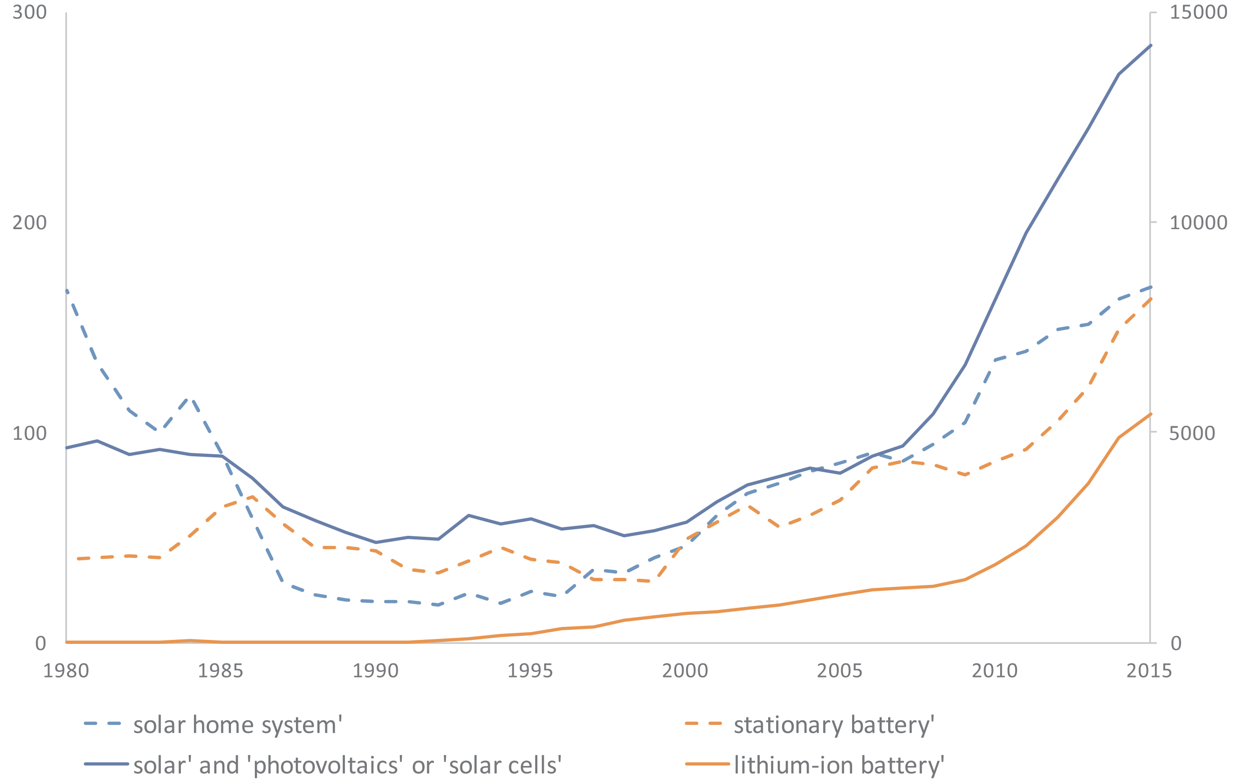

Fig. 9. Knowledge creation related to Off-grid technical components (deflated values with three years floating average). The dashed lines represent values for the primary axis, while values on the secondary axis are represented with the solid line. Search terms: 'solar home system', 'stationary battery',"('solar' and 'photovoltaics') or 'solar cells'", lithium-ion battery.

Source: scopus.com

urban areas as backup or alternatives to unreliable grids. Between 2009 and 2014, the price of SHS fell by 64% (Bloomberg New Energy Finance, GOGLA, & Lighting Global, 2016).

Over the last decade, Solar Pico Systems (SPS) have emerged as a new technology for powering appliances and lighting devices. SPSs often come as a set consisting of solar panels, a battery, a charging station, and an LED lamp. The price dropped by 75% between 2012 and 2016 and is expected to halve again between 2016 and 2020 (Bloomberg New Energy Finance et al., 2016). SPS technologies are now contributing significantly to the expansion of the off-grid market in the Global South (Bloomberg New Energy Finance et al., 2016; Lysen, 2013).

Also in industrialised countries, the idea of taking "the energy future into your own hands", that is, becoming energy independent at the household level, is increasingly popular (Elsasser, 2015; Sonnen, 2016). Innovative integration of PV in walls and windows of buildings, in textiles and all kinds of materials, open for new ways of designing electricity systems. Cost reduction, design thinking and branding make solar home batteries more attractive (Elsasser, 2015). In 2015, the American EV manufacturer Tesla introduced the PowerWall, a lithium-ion home battery that is designed to be paired with rooftop solar panels and enable consumers to 'go net zero'(Tesla, 2016).The PowerWall is a part of a new generation of batteries with the ambition of not only being automatized, compact and easy to install but also of becoming an interior wall-decoration.[2]

3.4.2. Actors and networks

Actors promoting the Off-grid electricity scenario vary in size, motive, geographical origin and organizational model. There is a clustering of actors in the Global South, where off-grid solutions are seen as a way to electrify remote and poor communities. Currently, the off-grid market is partly commercial and partly driven by donor financing and development aid. It includes private entrepreneurs, social entrepreneurs, charity organizations, international developing agencies and governmental agencies. Charity-based initiatives exist in parallel with business and distribution models targeting different customer segments in urban and rural areas.

At the global level, off-grid solutions are promoted by Sustainable Energy for All (SE4All), which was established in 2011 as an initiative under the United Nations. SE4All works to achieve universal access to clean and efficient energy sources for all humans and acknowledges that off-grid electricity systems are not a provisional solution, but rather an economically viable route to sustainable energy for all (SE4ALL, 2016).

Lighting Global was initiated by the World Bank to support the off-grid solar market targeting those without access to grid electricity. It brings together the World Bank, the Global Off-Grid Lightning Association (GOGLA), manufacturers, distributors and other development partners to develop the off-grid electricity market (Lightingglobal.org, 2016). GOGLA is an independent and non-profit industry organization with the overall mission to scale-up the off-grid electricity solutions sector (Bloomberg New Energy Finance et al., 2016; GOGLA, 2016).

In 2016, more than 100 private companies were providing SHS and SPS and approximately 20 companies offered "pay-as-you-go" financing mechanisms instead of payments in cash. Investment in the off-grid market increased 15-fold between 2012 and 2016. According to Bloomberg New Energy Finance (BNEF), the number of electrified off-grid households will grow from 25 million in 2016 to 99 million in 2020 (Bloomberg New Energy Finance et al., 2016; Zaripova, 2016a).

In places where the electricity grid infrastructure is fully developed, actors promoting Off-grid systems as a vision are often individuals or communities of individuals who aim to become independent from the centralised electricity system, avoid costly electricity bills, or simply take the sustainability transition into their own hands. Here we also find the emerging concept of "energy democracy" with its focus on social justice, sustainable development and grassroots mobilization (Angel, 2016; The Center for Social Inclusion, 2013). Importantly, internet and social media makes it easier to form grassroots initiatives that encourage others to join 'the off-grid movement'. The 'off-griders' usually communicate via websites that enable people from all over the world to share experiences in going off-grid. Off-grid.net, an online portal that encourages and supports people interested in building off-grid systems, is accessed by 75 000 visitors every month (in 2017), mainly from the USA and Great Britain. This webpage serves as a knowledge sharing platform and a news portal related to off-grid life-style. A special networking opportunity is the 'Landbuddy' section that serves for finding 'buddies' to go off-grid with (Off-grid.net, 2016).

In relation to off-grid solutions, some important innovative companies might influence the electricity system transition. For instance, the recently merged innovative energy businesses SolarCity and Tesla, create a vertically integrated energy company offering a single system for off-grid living. Together, they envision a future of a "one-stop solar plus storage experience" offering one installation, one service contract and one phone application (Hanley, 2016).

Many 'off-griders' live in the US, especially in those states where the electricity costs are very high and solar energy is abundant, such as Hawaii, Arizona, Nevada and California. Even though only 1% of US consumers lived off-grid in 2014, going off-grid is no longer seen as a rebellious step but rather as a decision of a savvy homeowner (Chediak, 2014). In Australia, a combination of high electricity prices and a high risk of electricity outages due to natural disasters creates favourable conditions for off-grid system (Parkinson, 2015; Zaripova, 2016b). In fact, Australia has the highest penetration of residential rooftop PV in the world and presents an attractive market for many companies specializing in battery technologies, such as Tesla, Bosh, Redflow, Samsung, LG and Sonnen. Since off-grid systems became a viable option, many local utilities and electricity suppliers offer a PV plus battery system combined with grid access in order to keep the customers connected to the grid (Parkinson, 2015).

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[2] The creative burst related to local electricity production does not stop at solar and battery technologies. An example of a novel wind power technology is the 'Vortex Mini' for domestic power generation, which has no blades, gears or bearings and looks just like a slim cylinder that oscillates or vibrates (Vortex, 2016).

3.4.3. Institutions

Besides increased performance and reduced cost of key enabling technologies, there are also examples of regulations that encourage individuals to leave the grid. The cost barrier for going off-grid can be reduced by subsidy schemes for PV plus battery systems, such as in Germany since 2013 and Japan since 2014 (Colthorpe, 2014; Enkhardt, 2016). In the first half of 2016, the Green party in Australia also proposed such subsidies (Gifford, 2016b). However, if the PV plus battery subsidy schemes are combined with reasonable FiTs (and if the seasonal variation of solar influx is larger), as they are in Germany or Japan, then it is more beneficial for the consumer to stay connected. This is, however, not the case in Australia or Hawaii where FiTs are very low and fees for houses with installed solar panels are high, making the off-grid systems increasingly cost-effective (Gifford, 2016a). As the Australian environmental minister Grent Hunt (in Parkinson, 2015) said: “it’s up to individuals”. Some consumers may leave the grid because of economic and regulatory issues, while others leave the grid in order to declare their independence or to directly contribute to the carbon-free electricity system (Off-grid.net, 2016; Parkinson, 2015).

In the countries of the Global South, off-grid solutions are often the only option; yet, these are usually not supported by formal regulatory frameworks. Formal institutions are therefore being substituted with innovative practices that are emerging in relation to all aspects of electricity provision. Through these practices, many actors attempt to enter the growing market for off-grid systems by adjusting to the context of poverty, no access to financial services from commercial banks, ineffective payment structures, gender inequality or criminality. To exemplify, micro-loans are often provided by microfinancing institutions to support diffusion of renewable technologies in poor areas; users are enabled to pay for services via ‘pay-as-you-go’ business models with help of ICTs; local communities are trained to ensure technical service and maintenance with a special attention to women; and technologies are designed to avoid theft. Such practices are often borrowed from other sectors, such as micro-financing, ICT solutions, water and sanitation (Adib, Gagelmann, Koschatzky, Preiser, & Walter, 2001; Sanyal, 2017).

4. Socio-technical overlaps

We have identified three different stylised alternative systems and traced the emergence and accumulation of a range of socio-technical components supporting these systems and how they take form at the niche level. We now turn to the question of how these components relate to the incumbent electricity regime, other sectors and discourses.

We can conclude that the Super-grid system configuration develops close to the existing electricity system, and can be characterised as hybridization processes. The global and continental Super-grid is enabled by incremental innovation in power transmission and supported mostly by regime actors such as national governments, research institutes and dominant firms that possess the capabilities to coordinate such megaprojects. At this point in time, visions, roadmaps and pilot projects seem to be particularly important to hold the main actors together and enable the top-down harmonization required for the centralised, border-crossing and capital-intensive transition to the global Super-grid. The vision alludes to ideals of control and efficiency (Lilliestam & Hanger, 2016) and link up to trends of economies of scale and globalism (Liu, 2015).

The Smart-grid seems to be emerging out of a combination of hybridization and niche accumulation. The Smart-grid system deviates from the dominant centralised system by creating a decentralised system configuration enabled by small-scale renewables and innovative communication, metering and storage technologies. Some technical components of the Smart-grid, such as ICT and batteries, which have primarily been developed in other sectors, have found niche market opportunities in Smart-grid development. Transaction technologies such as blockchain are borrowed from the banking sector. The parallel development of electromobility may both create demand for and enable Smart-grid solutions, e.g. via vehicle-to-grid systems. New entrants are increasingly contributing to the market for Smart-grid components and systems, and a range of public and private house owners and industries are becoming involved as prosumers directly contributing to Smart-grid experiments. Arguably, the Smart-grid scenario borrows legitimacy from other systems that build on networks of prosumers, most importantly the Internet, and from ideas such as the ‘sharing economy’, or the ideal market. However, governmental actors still hold a strong position in propelling the Smart-grid development by forming special organizations and financing demonstration projects. These projects most often involve incumbent actors such as existing DSOs, utilities and large power system companies, which are assigned to plan and carry out the project in collaboration with research centres and universities. Furthermore, in a transition period the relation to traditional power plants is complex, possibly allowing for some symbiosis with flexible gas power plants while being less compatible with coal and nuclear (see e.g. Göransson et al., 2017).

The Off-grid scenario is clearly an example of niche accumulation. It deviates from the regime by creating a highly disconnected and decentralised electricity system without the conventional utility grid infrastructure and electricity market. It is enabled by the rapid development of energy storage technology and small-scale renewables such as solar PV that, historically, have benefitted from a growing demand for electricity in remote areas and in mobile applications, in turn driven by progress in the aerospace, ICT and automotive industries. Currently, off-grid systems find growing markets in developing economies, where large-scale grid infrastructure is unreliable or non-existing. Since the current institutional frameworks offer very limited regulation of off-grid systems, practices are borrowed from other more established sectors such as ICT or banking. This has contributed to faster diffusion and easier maintenance in countries of the Global South. Over time, the perception of and vision for Off-grid systems has changed from it being considered a temporary fix until the conventional grid arrives, to a long-term solution with increasing economic and political strength and recognition. Moreover, the decreasing costs of solar and battery technologies make the Off-grid system scenario an increasingly feasible option even in countries with a fully developed electricity grid. Here, several innovative companies have found a growing market opportunity for stand-alone systems enabling off-grid living. The Off-grid vision in industrialised countries link up to quite different political and social discourses and ideals, including not only environmental responsibility but also social justice, individual independence and design-driven consumerism.

5. Conclusions

This paper represents an attempt to monitor the socio-technical transition in electricity systems around the world by mapping accumulation and alignment of structural components that indicate an initial formation of new alternative systems. The results make evident that there is indeed an ongoing transformation process, while its direction is not yet decided. We identify three distinct idealised transition endpoints: 'the Super-grid', 'the Smart-grid' and 'the Off-grid' systems. We find that all three alternatives have built momentum since the turn of the century through development of technology, mobilisation of actors, formation of networks and institutional work, as well as by linking up to the existing regime, the development in other industries and to various societal discourses and ideals. While the proponents of each scenario tend to articulate their vision as the most likely and beneficial future, we find it to be too early to announce 'a winner', i.e. a future dominant configuration, or even to clearly state in which direction in the design space we are heading. Some findings suggest that the future path will be closely aligned with the current electricity system and result in a 'greening of the existing system', while other findings suggest that the currently dominating system will be radically reconstructed.

A next step towards a deeper understanding of the ongoing transition processes would include a closer study of each system and the causal links between structural components to identify drivers and barriers enabling or hindering the breakthrough of each alternative system configuration.

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