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A global super-grid: sociotechnical drivers and barriers

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Abstract

Background: One way to design an electricity system wholly based on renewables is referred to as the global Super-grid, a vision of a transmission network of unprecedented geographical scope that uses advanced technology to balance spatially and temporally varying supply and demand across the globe. While proponents, since the 1960s, have argued that a global Super-grid is technologically possible and socially desirable, and significant technical progress has been made since the 1990s, development is slow with new transmission lines being built predominantly with established technology and within the boundaries of single countries. The aim of this study is to explore sociotechnical drivers and barriers of global Super-grid development.

Results: A main driver is the century old ideas that larger grids are more efficient and contribute to cooperation and peace. Over the last decades, the level of technical knowledge and networks of proponent have grown. The Super-grid also benefits from the potential opportunity of building on existing grids. Barriers stem from the scale of investments needed to experiment, path dependences in established industry and competition from novel smaller scale solutions based on local production, energy storage and smart grid technology. Other barriers originate in the organisational and institutional complexities of international electricity trade, and in the lack of trust at local and global levels, which hinder the development of necessary coordination.

Conclusions: The analysis suggests that if the Super-grid is to become part of a future electricity system, the discourse needs to open up, move beyond simplistic ideas of efficiency and 'technocratic internationalism', and take into account a broader set of social benefits, risks and trade-offs.

Keywords: Energy transition, High-voltage transmission, Super-grid, Technological innovation system

Background

Power system engineers have argued that an electricity system powered entirely by renewable energy can be attained by building transmission interconnections across the world and linking them into a global Super-grid [1]. A global Super-grid would be of unprecedented geographical scope and use advanced transmission technology to balance spatially and temporally varying renewable energy supply and electricity demand. Variants of this vision go back in history, with proponents dating back to the 1920s. In recent decades, it has attracted much interest among policymakers and members of the transmission industry, not the least as a solution to the climate crisis and need for rapid decarbonisation of the energy system. However, despite explicit international efforts to realise a global Super-grid, new transmission lines delivering remote renewable energy are being built predominantly within boundaries of single countries, or within limited regions.

The empirical scope of most previous studies is limited to specific projects or regional visions, such as the Desertec, Rustec, [2, 3], Gobitec [4], the US and Pan-European Super-grids [5, 6], Super-grid in the Americas

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[7], Eurasian Super-grid [8], Australian–Asian power grid [9], Europe North American interconnections [10] and China-EU transmission link [11] among others. Studies with a global scope remain scarce and mostly focused on techno-economic aspects [12–18]. Analyses with a broader sociotechnical systems perspective of the Super-grid at the global scale are still missing.

The literature on transnational grids provides a range of explanations for the weak progress towards the global Super-grid. A large part of the literature, based on an engineering perspective, claims that techno-economic aspects are not a barrier, blaming the lack of development on the 'politics' and unwillingness of nation states to commit [3, 19, 20]. Consequently, they urge national-level policymakers to put politics aside to allow for cost-efficient cross-border trading and flows of electricity. Since the inception of the Super-grid vision in the 1920s, advocates wished to depoliticise the transmission infrastructure in a spirit of 'technocratic internationalism' [21], i.e., the establishment of universal technological standards for grid operation, as an alternative to diplomacy and political negotiations.

Many social scientists, on the other hand, argue that this represents a too simplistic view of the socio-economic and political aspects of technological development. They insist one cannot eliminate politics from the equation or force politics to adapt but, instead, one needs to improve the understanding of the cultural and political complexities of the global transmission integration ambitions [3, 5, 22, 23]. Overall, this strand of research on Super-grid projects contributes important insights on factors that hinder development. Some conclude that it is a matter of nation states or a supra-national organisation to take the lead and commit to solving complex multi-stakeholder and jurisdictional processes required for the construction of the global Super-grid [3, 5, 24, 25]. Other researchers think that the global Super-grid is bound to fail, due to the 'megaproject'-related policy and management problems [4, 26], insufficient exogenous pressures on the industry [3] and increasing competition from other technological alternatives [4, 27]. There are also strong concerns regarding the possible social and ecological consequences of a project of this scale, which, critics argue, is bound to face a public opposition that fears ecological devastation, displacement of communities and a furthering of existing inequalities [20, 28, 29].

This study seeks to complement current literature with a systemic review of what drives and hinders the realisation of a global Super-grid. To that end, the Super-grid is analysed as an emerging 'sociotechnical' system [30–32], which performance and growth are shaped by the interplay between factors in technical, economic and political dimensions. By applying sociotechnical systems thinking, we attempt to pay equal attention to the techno-economic and the institutional–political dimensions, seeing them as co-constitutive. The normative questions of whether the global Super-grid is desirable or not, whether it could deliver on promised or imagined benefits, as well as what potential adverse or unintended consequences there may be, are outside the scope of this article.

Methods

Analytical approach

Inspired by Large Technical Systems [33], and Technological Innovation System (TIS) studies [34–36], the Super-grid is here analysed as an emerging sociotechnical system. To develop and function, a sociotechnical system requires a range of technical and social elements, including knowledge and material artefacts, actors and networks, as well as cognitive, normative and regulative institutions. Over time, such elements are organised into value chains linking production and consumption of a good [37, 38].

The TIS framework offers a model of how such systems grow, and a strategy of how to analyse factors causing system build-up as well as stifled development [36]. From a set of functions that describe system build-up, supporting and blocking factors are derived. The literature includes different lists of such functions, but they typically include innovation processes, such as knowledge development and diffusion, entrepreneurial experimentation, guidance of search, resource mobilisation, market formation and creation of legitimacy [36]. The supporting and blocking factors are located within the system or in its environment and can be related to technical, institutional and organisational dimensions of the sociotechnical fabric [30, 33, 37, 38]. Hence, a system can be blocked by missing technical knowledge and material artefacts; by a deficit of, or misaligned, cognitive, normative and regulative institutions that, hence, fail to incentivise and coordinate action; or by a lack of capable and devoted actors, and networks in which actors may share and develop collective knowledge, visions and norms. Alternatively, system growth is supported by the presence and continuous development of such components. In the research process the TIS functions were used to identify supporting and blocking factors (see Fig. 2 in Appendix) [36], but in the interest of accessibility and brevity, the "Results" section presents our findings only in the form of supporting and blocking factors.

Object of study and analytical scope

The global Super-grid is conceptualised as an emerging sociotechnical system, centred on a conceived value chain linking production and consumption of renewable electricity at the global scale. The global Super-grid

Table 1 Performed interviews

Role	Focus	Date
Professor at a European University, co-founder of REI & GEIDCO	Europe & Asia	Feb 1, 2019
Former CEO of the Desertec Industrial Initiative	Middle East, Europe and North Africa	Feb 13, 2019
Research Fellow at EC Joint Research Centre	Europe based & global analysis	Feb 15, 2019
Professor of electrical engineering at a European University	-	Feb 21, 2019
Senior Principal Scientist and Adj. Professor, corporate research at ABB	Europe	Feb 25, 2019
Professor of electrical engineering at a European University	–	Feb 25, 2019
General Manager at ABB China in Beijing	Asia	Feb 26, 2019
Former principal engineer at ABB transmission technology. Currently advisor for InnoEnergy	Europe & Asia	March 1, 2019
ABB China Corporate Research	China	March 14, 2019
Representative of Friends of Sustainable Grids (formerly Friends of the Super Grid)	Europe	March 22, 2019
ABB corporate research	Global	March 7, 2019
GEIDCO Europe representatives	China, Europe	April 10, 2019
Head of the Energy Systems Analysis at a European University	–	April 12, 2019
Director of Asia Renewable Energy Hub	Australia and Southeast Asia	April 15, 2019
Chief Technology Officer at the Supergrid Institute	France and Europe	May 24, 2019

constitutes one extreme alternative of many possible energy futures including more decentralised electricity systems as well as configurations where chemical energy carriers (such as hydrogen) take on a larger role at the expense of electricity transmission [39–41]. In this study we make no assessment or normative claim of the relative desirability or impact of any of these alternatives.

In the literature, there are at least two meanings attached to the term 'Super-grid': first, it refers to the spatial reach of transmission lines, where 'super' commonly means transmission over very long distances. Long-distance transmission often also implies cross-country connections resulting in regional or continental Super-grids with the visionary endpoint being the global Super-grid connecting suppliers and consumers on all continents.

Second, the Super-grid is also used to refer to technological capabilities at the system level, with some components and functions already existing and having 'Super-grid grade' capacity. In general, HVDC technology is considered a foundational component of the Super-grid, since it allows for the long transmission connections with lower losses. In addition, conventional point-to-point HVDC links are sometimes considered less Super-grid grade than the multi-terminal HVDC grid that enable load balancing between several nodes.

In this study, we use the term Super-grid to refer to large grids, crossing several countries, based on long-distance high voltage connections. In particular, we are interested in a grid spanning the world—the global Super-grid—as vision and logical end state, although its realisation is highly uncertain. While our primary spatial boundary is the entire globe, the developments at smaller geographical scales are observed as subsystems that may function as prototypes and building blocks of a global system. The global Super-grid is, however, qualitatively different from the country- and regional-level Super-grids, since it can take advantage of the synergies between time and climate zones across continents to balance electricity demand and renewable energy generation.

From a temporal perspective, the study in principle captures a system development since the creation of the early vision of continental grids in the 1920s until the beginning of 2020. However, the bulk of the analysis is focused on the last two decades, aiming at identifying supporting and blocking factors enabling or hindering the development towards a future goal—the full-scale global Super-grid. In this sense, it is a prospective study based on a retrospective analysis of historical developments and recent activities.

Data collection and analysis

The TIS analytical framework provides an overall frame which guided the research design and data collection processes. The analysis is informed by data from interviews, participatory observations, and desktop research. From February-May 2019, 15 semi-structured interviews were conducted with power system experts from leading companies, researchers and representatives from transnational industry organisations (Table 1). Most interviews were conducted remotely via virtual conferencing. To explore interviewees' perspectives on the Super-grid development process, open-ended questions were posed. All interviews were generally 1 h long.

Respondents were chosen for their expertise and involvement in Super-grid-related developments. Some,

Table 2 Literature review search themes and queries

Theme	Search query
Transition	Transition AND infrastructure AND (transnational OR "cross-border") AND NOT corporation
Innovation	Innovation AND infrastructure AND (transnational OR cross-border) AND NOT corporation
Innovation system	Innovation AND system AND (transnational OR "cross-border") AND NOT corporations
Megaproject	Megaproject AND infrastructure AND (energy OR transnational)
Energy infrastructure	Infrastructure AND energy AND (megaproject OR transnational)

but not all, respondents are proponents of the Super-grid. They provided a range of perspectives on the topic, but techno-economic perspectives dominate. The geographical coverage of respondents was limited by access to experts willing to participate. Interviewees come mostly from Europe, Asia and Australia, while respondents from Africa and America are lacking.

In addition to the interviews, the first author conducted participatory observations during the International Council on Large Electric Systems (CIGRE) International Symposium, and the International Smart Grid Action Network workshop in June and October 2019. Participation in these events helped improve contextual understanding and experience first-hand the ongoing discussions among actors in the sector.

All interviews were recorded, transcribed and analysed using the Visual Understanding Environment software as a coding tool to categorise data thematically based on the TIS functions. Participatory observations were added to the data analysis in the software.

A second phase involved literature review of secondary sources (scientific literature, industry reports and web-based news articles). The review was performed in Scopus, using different search terms and combinations (Table 2). The search was deliberately filtered to the subject areas of business, energy, social and environmental sciences to complement the techno-economic perspective of respondents. This expanded the analysis and provided a good overview of the (so far limited) body of literature that dissects the topic from a social or environmental science perspective.

This search resulted in 447 publications, including duplications across searches. After reviewing publication titles, the selection was reduced to 107 publications and after reviewing abstracts, the selection was further reduced to 40 publications. The final selection was reduced by half after excluding gas infrastructure-related papers. This selection was expanded again by relevant publications found in the reference lists of the selected papers. The final selection can be found as references in this paper.

The selection of industry reports was based on 'snowballing' from findings in interviews, observations, and scientific literature. Findings from secondary sources were added to the primary data analysis in the software. While potentially limiting the depth of the analysis, the use of a broad range of data allowed us to get an overview of an empirical field at the global scale of observation.

Results

Factors supporting the development of a global Super-grid

In the following four sections, the emergence and evolution of supporting factors are reviewed. The first section discusses cognitive–normative institutions or rationales that motivate Super-grid development, the second, technical capabilities that would enable it, the third, accumulation of actors and formation of networks that develop knowledge, advocate system build-up and experiment, and the fourth, the materialisation of actual gridlines that form physical building blocks. There is a built-in chronology in the text to indicate a certain stacking of factors over time.

Legitimacy built on century-old arguments

The stated benefit of a global Super-grid is mainly based on two arguments, one related to efficiency and the other to peace. These appear to be widely shared within the transmission industry and professional community of electrotechnical engineers [42, 43], and both have deep historical roots.

The idea that a larger electric grid enables a more efficient system is as old as the grid itself and has come to form what could be called a 'natural trajectory' within the transmission industry [44]. The logic runs: the larger the grid, the more efficient matching between electricity supply and demand.[1]

At the beginning of the twentieth century, longer gridlines enabled electricity supply from large-scale hydro and coal power plants outside of the demand centres. With more consumers on the same grid, demand was also evened out, and hence easier to match to supply.

[1] This conclusion is based on a taken for granted premise explicitly stated or just assumed by many interviewees, reviewed articles and reports. For an historical account see [21].

Over time, local grids were connected and evolved into national grids, and in the 1920s, ideas of continental grids emerged, such as the "European Super Power System" proposed by the German engineer Oskar Oliven [21]. In the mid-1960s, the architect and futurist Buckminster Fuller envisioned a global grid [45, p.189–191]. The global grid was imagined to balance the supply and demand for electricity across regions and time zones. Fuller [46] later developed a detailed vision, where the world's electricity demand is covered by renewable energy from distant locations [43]. Small pockets of the electrotechnical community nurtured Fuller's vision in the 1980s and 1990s, e.g., the Global Energy Network Institute [47]. In 1992, Gunnar Asplund at the electric power company ABB gave new life to Oliven's and Fuller's ideas and proposed an electric grid stretching across Europe to North Africa transmitting solar power from the South, hydropower from the North and wind power from the West [48, 49].

With the advent of new transmission technology (see below), and the growth of renewable energy, collective expectations and beliefs about the Super-grid as the only technologically and economically viable solution for a future system based on 100% renewables spread within the transmission industry [50]. The Super-grid gained its legitimacy through an historically proven 'standard of good practice' in the transmission system development, i.e., building large scale power plants and connecting them to demand centres. Super-grid advocates share a strong belief that transmission extension and integration is cheaper and more efficient than smaller scale local solutions to match demand and supply [51].

Super-grid advocates have also expressed expectations of the political implications of global electricity interconnection. In the words of an interviewee: "a transmission line is a perfect symbol of cooperation" [50]. They argue that high levels of cross-country interdependence are necessary to create new patterns of energy security featuring cooperation, mutual benefit and win–win results that could defeat current separatist and protectionist political tendencies [43]. Based on a different interpretation, the logic can also be described as a "deterrence strategy", meaning that collaboration is achieved through fear of compromising system security, as failure would affect parties at both ends of a grid connection with blackouts, and the rest of the system with load imbalances [50, 52]. The idea that technical infrastructure crossing state borders forms a more efficient pathway to prosperity and peace than politics and diplomacy has been termed 'technocratic internationalism' [21]. It was evident already among the advocates of a European grid in the 1920s and 1930s. Half a century later, Fuller clearly expressed the idea: "I, therefore, predict that before the end of the 1980s the computer's politically unbiased problem-solving prestige will have brought about the world's completely integrated electrical-energy network grid. This world electric grid, with its omni-integrated advantage, will deliver its electric energy anywhere, to anyone, at any one time, at one standard rate" [46, p. xxxi], and it will "cancel out the ideological differences of the respective beneficiary peoples" [45, p.190].

Technological enablers of larger and more flexible grids

The early visions of grid extension guided technical development, and the advancement of technology in turn expanded the ambitions and spatial scale of the visions. From the engineering perspective, the size of the grid is only limited by available transmission technology. The most important technical parameter is the voltage level, since the cost-efficiency of the transmission line length depends on power losses that are inherently linked to voltage.[2] Since the inception of the electricity system, maximum voltage level and length of gridlines have grown in parallel, from 10 kV and 10–100 km in the 1880s to about 1000 kV and 3000 km in the 2010s.

There are two types of high voltage transmission technology. High voltage alternating current (HVAC) became the dominant design in the early days of the industry, since it is easier to transform AC to high voltage levels. Still in 2019, HVAC accounted for some 97% of high-voltage transmission in Europe [53]. For most part of the twentieth century, high voltage direct current (HVDC) remained expensive and was only applied in niche applications, such as sub-sea cables. However, while the cost of voltage conversion at the terminal stations are higher for HVDC, the cost components dependent on link length, such as losses and cable diameter, are lower for HVDC. Hence, there is a break-even length, where HVDC becomes the low-cost option. This length is significantly shorter for underwater and underground cables. HVDC is also more flexible in terms of connecting power sources and grids with different characteristics. Hence, HVDC is the preferred option for Super-grids and the interest in connecting large remote solar and offshore wind farms strengthened the motivation to improve HVDC technology.

With a new generation of power electronics, HVDC became competitive at the turn of the twenty-first century. ABB introduced HVDC Light in 1997, based on Voltage Source Converter (VSC) technology, which solved some technical problems, reduced costs and simplified electricity exchange in both directions [51]. The advancements in multi-terminal HVDC grids enabled

[2] To transmit the same amount of power a higher voltage means a lower current and hence less resistance losses.

connections between three or more grids [54] as well as allowed for both full-length and segmented operation that eliminate the risk of whole system shutdowns [11]. These technologies, considered to be of Super-grid grade, increased the feasibility of very large transmission grids that balance varying supply and demand over great distances. The advancements in HVDC technology thus directly correlated with increased ambitions to build a global Super-grid.

Growing knowledge networks and advocacy coalitions

Since the turn of the twenty-first century, the Super-grid system build-up has moved beyond visions and development of technical components. New actors have joined the network of Super-grid advocates to initiate real-world projects. Besides the early mover ABB, other power equipment manufactures from Europe, North America and Asia have joined the race of technology development [51].[3] The growing number of manufacturers have resulted in continuous technical improvements, lower prices and increasing demand [55].

Technology manufacturers have also played a key role in promoting Super-grid visions around the world. The vision of a 100% renewable European Super-grid developed at ABB in the 1990s inspired the Desertec project [49]. Desertec, established in 2009 by industrial actors and researchers from Europe, the Middle East and Northern Africa, planned to build an HVDC connection supplying Europe with solar electricity from North Africa. Though the Desertec project was never materialised, it broadened the range of interested actors and spurred network formation.

In parallel, the European Commission showed interest in a European Super-grid, as a viable solution to achieving the EU's ambitions to increase renewable energy generation and integrate the electricity market across its member states. With a supranational political structure now in place in Europe, the idea from the 1920s of using the electric grid as a unifying transnational infrastructure gained momentum. In 2012, the e-Highway 2050 initiative was launched, aimed at incentivising researchers, transmission system operators (TSOs) and manufacturers to evaluate the feasibility of an integrated European transmission network for renewables by 2050 [56]. Around the same time, "Friends of the Supergrid" (later "Friends of Sustainable Grids") was established as a network of European equipment manufacturers, TSOs, utilities, investors, developers and consultants to advise the European Commission in the planning process [42]. In parallel, specialised research institutes were established, such as the Supergrid Institute in France [57].

ABB's vision also influenced developments in Asia, where following the Fukushima accident in 2011, electrical power industry actors and investors sought alternative solutions to eliminate their reliance on nuclear power [49–51]. A Japanese entrepreneur and investor Masayoshi Son established the Renewable Energy Institute as a platform to explore the possibility of building an Asian Super-grid—a vision to transmit wind power from the Mongolian Gobi Desert and hydropower from Russian Irkutsk with HVDC grids to customers in megacities, such as Shanghai, Seoul and Tokyo [49, 50]. The institute was joined by Mongolian, South Korean and Russian power companies as well the State Grid Corporation of China (SGCC) in leading and financing the Asian Super-grid initiative [58].

In 2016, SGCC established its own organisation, the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) to promote what was called a Global Energy Interconnection [58, 59]. When the Chinese government in this way became a supporter of the global Super-grid, it resulted in accelerated knowledge development and an extended network of proponents. Through the 2010s, GEIDCO hired 2000 engineers and funded more than 300 professors and 1000 graduate students at Chinese universities to investigate and develop advanced transmission technologies [60]. Between 2000 and 2019, Chinese researchers accounted for 41% of all publications recorded in Scopus on multi-terminal HVDC grid technology, and in 2018, GEIDCO founded a scientific journal, 'Global Energy Interconnection.'

GEIDCO has been actively lobbying industry actors and governments around the world and has to this purpose set up seven regional offices on all continents to open and coordinate dialogue among national governments [43], as well as to offer ready-made packages of continental Super-grids to countries around the world [61, 62]. GEIDCO has also established presence at the United Nations and became an official partner at COP24 in 2018, and as a result, the Global Energy Interconnection Action Plan became part of the global agenda document [63]. The Chinese government believes that their "political system with central governance is the most suitable for the Super-grid" [43]. Some interviewees praised the 'holistic control' and long-term economic planning of the Chinese government and its success in demonstrating the most advanced transmission technologies [43, 51, 64].

Following China's activities, the European Commission initiated the research projects 'Migrate' and 'Promotion' to encourage European actors to investigate

[3] For example, Siemens, Alstom and Prysmian in Europe, General Electric from the US and the Asian companies Hitachi, Mitsubishi Electric, NR Electric and a range of Chinese power companies.

multi-terminal HVDC technology [65, 66], and feasibility studies of grid connections between Europe, North America and Asia [6, 10–12, 67].

The widespread interest in the Super-grid vision in the transmission industry was apparent when it became a focal point of discussions in the International Council on Large Electric Systems (CIGRE). The council was established already in the 1920s and connects transmission and distribution system operators, researchers, decision-makers and manufacturers from 90 countries that meet and exchange knowledge during annual conferences. In 2016, it established a dedicated working group to carry out a feasibility study by experts from all continents, on the techno-economic challenges and benefits of a Global Electricity Network [68].

Piecemeal materialisation link by link

Chinese actors have been the most willing to take risks associated with investments based on Super-grid technology in exchange for becoming a global market leader [29, 69, 70]. In 2019, the SGCC commissioned the world's longest HVDC connection of 3300 km between the North and East of China, the Changji-Guquan, [71]. In addition, SGCC in 2019 selected ABB to construct the Zhangbei project demonstrating the largest multi-terminal HVDC grid, a potential technological prototype of the global Super-grid [51, 72]. Transmission industry leaders from ABB expressed excitement about China-led demonstrations as these created an important benchmark for their technology: "In all humbleness, ABB proposed the Super-grid vision already 25 years ago and this is the first time it is being demonstrated" [51].

With a significant interest in building the global Super-grid, GEIDCO has been providing financial support to other countries, especially if those are included in China's 'Belt and Road'[4] infrastructural initiative [73]. The Chinese government had plans to provide an investment of \$27 trillion by 2050 for the construction of the electricity infrastructure, with \$7 trillion alone going into constructing cross-country transmission connections [72, 74]. As a GEIDCO representative explained, Africa is viewed as a suitable place for demonstrating the first continental grid as part of the initiative, and GEIDCO is providing substantial financial assistance to materialise it [43, 75].

The materialisation of a continental Super-grid in Europe has a different starting point. It is not a process of building an entirely new system, as in much of Asia or Africa, but an improvement of a transmission grid already built and synchronised across countries [43, 50, 56]. In support of more integration, the funding instrument Connecting Europe Facility tried to break the nation-level investment schemes by providing loans to investments in cross-border connections [76]. The EU also provides a platform for member state negotiations. For cross-country connections specifically, the European Commission in 2013 created the Project of Common Interest framework to evaluate proposals and overlook their construction. The framework provided the benefit of faster permission processes and improved regulatory treatment for selected projects, resulting in several point-to-point interconnections between countries [77].

As in the EU, in regions with already established supra-national cooperation, such as the Association of Southeast Asian Nations and the Gulf Cooperation Council, there have been some progress in constructing and integrating transmission infrastructures between countries.

Factors blocking the development of a global Super-grid

The following sections review blocking factors, subdivided into five parts. The first three relate to the technological limitations and uncertainties that together with competition from mature transmission technology and emerging distributed electricity systems, negatively affect experimentation and investment in Super-grid grade technologies. The fourth part highlights the slow development of gridlines crossing borders between nation-states and regions and trace the root course of this to a lack of supra-national institutions. Finally, the fifth part discusses the lack of trust and negotiations between stakeholders at local and global levels that would be required to increase the legitimacy of the Super-grid and the development of necessary institutions.

Technological limitations and uncertainties

Though the technical and economic feasibility of a global Super-grid has increased, current technology is not without constraints. For example, onshore HVDC lines are limited to about 3000 km long sections. In a study from 2017, Ardelean and Minnebo [11] conclude that connecting western China and eastern Europe, some 6500 km, was economically inefficient, as each segment of HVDC lines requires a VSC converter, each of them increasing losses and costs [19, 67]. In addition, capital costs are highly dependent on parameters, such as local environmental constraints, geography and population density. A need to cross mountainous regions for example, could increase costs substantially [78].

While there is need for further technical development, the physical scale of transmission lines makes it difficult to experiment with and demonstrate new Super-grid technology. Due to high upfront capital costs, long lead

[4] The Belt and Road Initiative is a global infrastructure development strategy adopted by the Chinese government in 2013 to invest in nearly 70 countries and international organisations. It is often referred to as the twenty-first century Silk Road.

times and permission processes, testing and constructing new transmission lines is a lengthy and expensive process, in which each stakeholder must make a long-term binding commitment [51]. Researchers repeatedly refer to the risk of getting locked-in to the wrong technical design in a context of a rapidly changing and uncertain energy transition process, as a key barrier to experimentation. Decision-makers are hesitant to commit to 10–20 years of technology demonstration and taking the risk of transmission connections becoming obsolete before they commence operation [3, 4, 27].

In this process, it is also unclear how much and which of the existing HVAC transmission connections should become a part of the Super-grid [64]. While some propose combining existing HVAC grids with new HVDC links to decrease costs [78], others make an opposing claim, arguing that integrating the existing HVAC with the new HVDC technologies is difficult and costly [27, 49]. An expert from the Supergrid Institute emphasised that a shift towards multi-terminal HVDC grids is necessary to isolate failures and avoid the 'domino effect' of widespread blackouts [57].

Path dependent technology choice

Technological uncertainties create a disadvantage for Super-grid grade HVDC technologies in relation to the more mature HVAC transmission technology, that is perceived as less risky. According to Gold [79], new transmission network developments are not hindered by a lack of investments in general. Instead, path-dependent development, especially in Europe and the US, dictates resource mobilisation. The majority of investments go into upgrades based on mature transmission technologies, while the investment in cutting-edge HVDC technologies is still small and allocated mostly to R&D and in-house technology trials [27, 51, 57].

In North America, the US finds itself in a pressing need of upgrading its ageing transmission infrastructure built in the early 1900s. However, attempts to build new HVDC transmission grids and interconnections have had little success, especially where these threaten to make present grids and electricity production plants obsolete [80]. This was the case for the Clean Line project based on transmission lines that could supply coastal demand hubs with wind power from the centre of the country. It was met with resistance from established TSOs and power producers with vested interests in the existing infrastructure [81].

In Europe, cross-country interconnections are still largely demonstrated using more mature HVAC and HVDC technologies, rather than multi-terminal HVDC grids. European experts are concerned that focus on mature technologies will harm Europe's technological capabilities, as the EU is believed to lag 20–30 years behind China in demonstrating the most advanced HVDC technologies [57, 67, 82, 83].[5] In the words of an interviewee: "In Europe, we are too concentrated on being the first to achieve transnational interconnections based on the goal of the European Commission, but we need more multi-terminal HVDC grids" [57]. Similarly, the grids in South East Asia and the Gulf region are to a large extent built with HVAC technologies, while construction of new HVDC links is a part of future plans [84–87].

Rise of technological alternatives

Besides the rivalry with more mature transmission technology, the Super-grid solution also meets increasing competition from local 'smart' distribution grids and off-grid systems enabled by ICT, solar panels and batteries [27, 39]. By allowing for thousands of parallel experiments, these smaller scale and modular technologies enable faster learning and cost reduction. In the EU, for example, grid digitalisation, storage and demand-side flexibility compete successfully with grid expansion, given that these require less upfront investment, have shorter lead time and are not heavily reliant on governmental commitment [49, 88, 89]. As the author of ABB's Super-grid vision said: "I used to work with transmission technology, and I work with batteries now and there is a reason for it, because I see that the trend is going in favor of batteries. In sun-rich areas, we can already see batteries used for balancing, they do not use the grid for it. (…) There is so much money put into batteries that it's unbelievable" [49]. The CEO of Desertec has also refocused towards supporting demand-side solutions: "The aspect that is often forgotten is to start bottom-up and bringing more flexibility to the demand side" [88].

In rural regions, particularly in sub-Saharan Africa, where there is very little grid infrastructure to start with, small scale energy solutions may be even more competitive [90]. The prospects for large Super-grid experiments is worsened by the general lack of financial capital and an immature transmission industry that struggles to recover its costs under unreliable financial schemes, a situation someplace worsened by corruption [91].

Missing global institutions

In the 1930s the plans to develop a European grid failed because of growing nationalism and the interest of nation-states to keep control of critical infrastructure.

[5] Projects exploring multi-terminal HVDC grids such as 'PROMOTION' (Progress on Meshed HVDC Offshore Transmission Networks) and 'the North Wind Power Hub' are still in the research and planning stage, with the actual construction expected in the next 20–30 years.

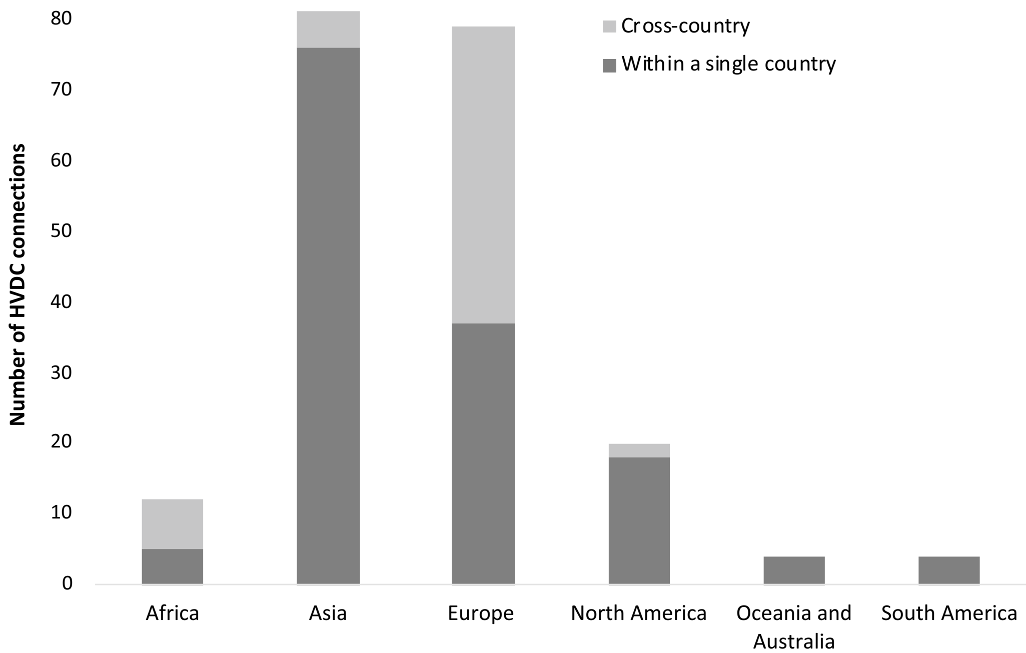

Fig. 1 Overview of HVDC connections in different regions. Data include existing connections as well as those under construction. Year: 2019. Source: Ardelean and Minnebo [11], Hassanpoor [95]

Nationalisation of electricity systems, hence, came to dominate the twentieth century. More recently, attempts to construct interconnections across countries and continents have, again, repeatedly failed.

The first example of an inter-regional project to connect European and North African countries, the Desertec, ran into a stalemate in 2014. According to interviewees, it failed due to a top-down approach of European stakeholders, who planned to construct large-scale solar parks in the Sahara region to supply Europe with cheap renewable electricity, without involving stakeholders in North Africa in designing the project [50, 88].

Another example of a failed inter-regional construction effort was the HVDC connection between Australia and South–East Asia that were to supply Indonesia's growing demand with cheap solar electricity from remote areas in Western Australia. It failed due to political disputes and lack of economic integration of the regions and thus could not demonstrate the benefits of the inter-regional connection [9, 92, 93].

While China has demonstrated advanced 'Super-grid grade' technologies within its own borders, it has been less successful in integrating domestic systems with other countries in Asia and beyond. The intention to focus on connecting national grids to other Asian countries, as well as to Europe and Africa had in 2020 not gotten beyond the planning stage [29, 58].

As is evident from Fig. 1, the American continent has very few cross-country HVDC connections. While the industry in the US has been investing heavily in transmission grids, the incentives have been stronger to upgrade existing domestic assets than to invest in cross-border connections. While Brazil is home to the second longest HVDC connection, South America has not seen major developments in cross-country HVDC interconnections.

In Africa, the number of cross-country interconnections is increasing, albeit from a low initial level. Since 2016, the African Development Bank has launched the initiative 'Light up and Power Africa'[6] to support expansion of transmission electricity grids, many of which aimed at increasing cross-country electricity trading [94].

The majority of cross-country connections are located in Europe (Fig. 1), enabled by the EU and its institutions promoting pan-European cooperation and ambitious goals to increase the share of renewable energy.

These examples indicate that whether cross-country connections are built or not, to a large extent depends on institutional factors. Sociotechnical systems benefit from well-developed institutions, such as: (a) technical standards that ensure interoperability between components; (b) established market mechanisms that distributes costs

[6] There are ambitions to increase on-grid transmission and grid connections by 160% by 2025, with the majority of funding coming from the governments of USA and China.

and benefits in a way accepted by all actors; (c) incentives that ensures investments; and (d) trust in other market actors and authorities that they will not violate agreements or arbitrarily change rules at a later point in time. For systems confined within single countries, the state typically creates and upholds such institutions, but at the global level there is no superior authority that can enforce rules. Hence, the global Super-grid lacks key institutions and there is no clear path forward. The first three categories are discussed in this section, while trust is the topic of the next.

While lack of international technical standards has been pointed out as a barrier [4, 20], it is likely not the biggest challenge. The technical potential of the new HVDC technology to link national systems with different power specifications reduces the need for a strict global standard. In addition, there are international organisations developing standards. In Europe, the European Network of TSOs develops network codes, while CIGRE and the European Committee for Electrotechnical Standardisation are responsible for developing standards for the Super-grid [96]. In Asia, GEIDCO's research team is working on identifying potential global standards [56].

Regulation of markets and value distribution, as well as investment incentives, pose more difficult problems [20, 27, 92]. The techno-economic models that are used to demonstrate the viability of a global Super-grid are based on maximised value creation at the global system level, which would correspond to either a market controlled by a single, rational system planner, who optimises for global-level lowest system costs, or perfect markets, where all actors have the capacity, information and incentives to act in a way that replicate the same optimisation [97]. In practice, the Super-grid would, however, connect many private and public asset owners, operators and end-users with varying incentives, information and capabilities scattered across multiple market structures and jurisdictions.

Even if there is potential value created at the system level, it is unclear how individual actors would appropriate parts of it. How to create new market relations as well as share costs and benefits in a Super-grid that crosses borders remains to be solved [20, 27, 97]. Tasks such as balancing services, capacity allocation, congestion management, and infrastructure maintenance are traditionally planned and coordinated at national levels. There is no authority that can redistribute tasks, costs and benefits at the global level [20].

In light of the economic benefits, promised by techno-economic models, that could be gained if only the right global institutions were in place to solve coordination problems, some authors have suggested that a 'Global System Operator' [14], or a 'United Nations Renewable Energy Organisation' [98], needs to be formed. However, it is far from clear on what principles and ideology such an organisation could be established and legitimised. In addition, the mere presence of a transnational market executor is no guarantee for strengthened cross-state cooperation as the common energy market still has to become the priority at the national level [19, 27, 99]. Hoffrichter and Beckers [100], observe that a centrally planned EU market could lead to resistance and withdrawal of participant countries as it is unlikely to account for all national differences related to, for example, energy security, industrial structure, and preferred energy sources.

Solutions hence need to be formed in negotiations between states. However, some states may not win anything [92]. If a global electricity market creates value at the system level but a potential loss at the national level, from a state's perspective, there is little incentive to cooperate. Obvious market losers, such as transit countries, are likely to oppose the development of a Super-grid unless there is an attractive compensation mechanism [1, 52].

Lack of global level institutions also affects project funding. Mobilising secure financing for interconnections between countries and regions is difficult due to the absence of a coherent global financing mechanism. As transmission networks historically have been built to serve national markets, a strong relation between the state and the electrical power industry has emerged, through which TSOs could obtain investment backed by the national government and paid by tax money, in exchange for reliable electricity provision [99]. This further strengthen the path-dependence discussed above. As a consequence, both state-owned and private investors tend to prioritise investments in national grids [101].

Disconnected proponents and geopolitical concerns

Overcoming the institutional deficiencies pointed out in the previous section would require a strong backing of the Super-grid vision. However, there are signs indicating that the vision has failed to gain legitimacy, where a key component is lack of trust between stakeholders.

The Super-grid vision and plans have been developed within the well-established network of transmission industry actors with ability to manage the scale and costs associated with developing and demonstrating Super-grid technology [27]. The vision has thus been shared among a small group of firms and regulators, who have designed and planned the Super-grid without much interaction with actors in the rest of the system, such as local political organisations, electricity producers and retailers, and civil society [4, 22, 92, 102–104]. This exclusiveness has led to a lack of debate and scrutiny of established logic and practices, hindering the ability to accommodate opposing views and adapt plans.

As a result, the vision has had mixed success in gaining legitimacy outside the network of its strongest promoters. Interest from national policymakers has been inconsistent and Super-grid advocates display frustration with weak political support. The "biggest barrier is the limited governmental commitment that is limited to 4-year intervals, while an off-shore project take minimum 9 years", according to a representative of the North Sea Wind Power Hub[7] [82]. In addition, public opposition has managed to politically de-legitimise Super-grid development [5, 20, 105]. New transmission grid projects have historically experienced public resistance and critique for lack of public consultation [28, 105]. The GEIDCO representative expressed negative sentiment towards public consultations that "make the transmission network development difficult and slow", and transmission projects in Europe are hard to realise, because "environmental concerns of the public are taken too seriously" [43]. China-led projects in other parts of the world have, however, not escaped resistance from environmental organisations. About 14% of Chinese infrastructural projects in 66 countries have faced some kind of local pushback since 2013 [29, 106]. Public consultations have not been included in GEIDCO's activities, and projects have proceeded to construction in spite of strong local opposition [29].

Consequently, the international community is increasingly critical of China's Super-grid strategy. Despite GEIDCO's efforts to increase global legitimacy of the Super-grid vision, scholars and journalists warn that the institutionalisation of a global Super-grid could provide means for authoritarian regimes to reinforce their practices, to reorder global power hierarchies and obtain geopolitical dominance [4, 5, 59, 103, 107].

The concern about China using the Super-grid to obtain geopolitical dominance increased after the country created the global version of the Asian Super-grid vision, and redraw initial grid lines to fit the Belt and Road Initiative [59]. Critics are also speaking up about the risks of turning a blind eye to the social and environmental implications of having an undemocratic government as a system builder in the belief that engineering solutions are able to resolve political issues [4, 92]. While Chinese investments are welcomed in many countries that are vulnerable to persistent electricity shortages, critics warn that China's generosity represents a neocolonial strategy to gain control over natural resources, via infrastructure funding and ownership. For illustration, SGCC has become a large utility shareholder in Brazil, Chile, Philippines, Portugal and Greece [108]. With a key role in other countries' energy systems, it is argued that China gains the ability to exert influence on national decision-makers, potentially making them a part of a Chinese controlled Super-grid [109].

With mounting concerns about Chinese dominance in the global economy and international politics, many decision-makers, particularly in western societies, are hesitant to support the global Super-grid. National governments are reluctant to compromise their energy security, political control and military strength in exchange for an allegedly cheap and efficient electricity system [4, 92]. A GEIDCO representative admitted that their global vision had achieved little success in the USA due to worsening relations with China [43], and territorial disputes between China, Japan and South Korea pose a significant barrier to the construction of a regional network in Northeast Asia [52]. Worry about unwanted dependence via electric grids is not merely related to Chinese ambitions, or to new grid connections only. To break free from Russian power supply and associated Russian political influence, countries in the Baltic region plan to disconnect from the former Soviet transmission network and instead connect to the EU grid [110].[8]

Discussion

The Super-grid is sometimes portrayed as the natural, or even inevitable next step in the development of electricity systems. It follows the logic that the larger the grid, the easier it is to balance supply and demand and optimise the system, and hence society will follow a path towards continental and eventually global grids. The logic of this 'natural trajectory' is often accompanied by 'technocratic internationalism', a view that technical systems crossing borders will bring about peace and prosperity and somehow replace politics and diplomacy [21].

Our results indicate that the development of a single globally interconnected electricity system is far from a given. Instead, system growth is uneven and fragmented across the world. Experimentation and construction of long-distance connections and Super-grid components are mainly carried out within nations. In some regions, such as northern Europe, countries are strengthening their cooperation through building cross-border transmission [111]. However, spatially scattered and locally shaped Super-grid developments are currently creating a

[7] A proposed energy island complex to be built in the middle of the North Sea as part of a European system for sustainable electricity.

[8] During the review process of this paper, in the spring of 2022, Russia invaded Ukraine. This will likely significantly affect the development of energy infrastructures in Euroasia in many years to come. The issue of trust, or lack thereof, will most surely be of utmost importance.

variety of system designs and business models that might not easily be combined into one system. There are also competing visions of what is a desirable endpoint for Super-grids—should these be regional or global, based on Western ideals of liberal democracy and market capitalism, or Chinese centralised governance? The sociotechnical analysis presented here challenges the technocratic view and demonstrates that neither the technical nor the organisational and political issues are simple and straightforward.

From a technical viewpoint, HVDC technology as it has developed over the last three decades represents the means that enable continental and global grid connections. While there are still technical difficulties to overcome, experiments with so called Super-grid grade technology are conducted and the number of long-distance connections are increasing. However, the large investment and long lead times of each project result in slow learning processes, compared to smaller scale modular energy technologies. As shown in other studies [39, 41, 102, 112], the Super-grid is not the only future alternative and other system designs based on smaller scale technologies are developing fast. Hence, more flexible distribution grids ('smart-grids') and local energy production and storage have become direct competitors to transmission grid extensions [4, 39, 113]. In addition, while there is resistance to all types of new construction projects, very large-scale projects demand political coordination to a much higher degree. This implies that materialising regional or inter-continental Super-grids depends on stronger political will and commitment, and readiness to bulldoze over local interests.

An advantage of the Super-grid vision is that it is backed by actors rooted in the existing value chain with access to large resources. The incumbent transmission industry and strong private–public networks seemingly provide a head start through access to grids, technological expertise, and funding. However, in most industrialised countries, transmission grids co-developed with the nation state in the twentieth century and international connections have been a contested issue since the birth of the industry. The transnational Super-grid is hence in competition also with the nation-state-centred systems of the past and present. Moreover, while complementing existing HVAC grids with new HVDC interconnections allows the industry to have a solid starting point for materialisation, the link to the established system can also slow down development due to vested interests and bounded rationality. In many technological fields, innovation is driven by new actors with path-breaking ideas that can challenge systemic lock-ins. The strong embedding in incumbent industries then appears as a disadvantage. The scale of investment in each experiment, required connections to existing grid infrastructure, and access to planning and permission processes, create formidable barriers to entry for newcomers and form strong material, organisational and institutional path-dependence [114].

The findings suggest that moving from national to international grids also requires new forms of market and value appropriation in the electricity value chain. Since there is no supreme power or universal way to handle conflicts and trade-offs at the global level, there is no simple solution to this problem. This points to the larger geopolitical questions surrounding the global Super-grid. There are fears that the development of dependencies and need for global standards will not at all result in a system automatically generating benefits for all, once dreamt of by Buckminster Fuller, but a system dominated by a small number of powerful actors creating economic and political benefits for some. Through the course of history, governments have been using electricity infrastructures to achieve not only economic but also other political goals [21]. This is likely a reason why China's effort to reduce variety by providing a standardised Super-grid design for all regions of the world is perceived as a suspicious political move.

On a theoretical note, we observe that most studies either take a techno-economic perspective or focus on the political and institutional barriers to the Super-grid trajectory. The core assumption of the sociotechnical systems thinking applied here, however, is that technology and society co-evolve, and symmetric attention to social and material dimensions, therefore, enables a more complete analysis. In addition, this study is one of a few sociotechnical studies applying a global system boundary. Compared to studies with a national system boundary, it finds among other things that the nation state shifts from being a unique actor with specific and far-reaching institutional capacity, to one actor among many that needs to navigate a larger sociotechnical landscape of international politics and economy. To make sense of the energy transition and other processes of sociotechnical change in a globalised world, we see a need for more studies at this scale of analysis. One drawback of the wide geographical scope is the challenge of collecting primary data. A limitation of this study is the lack of interview data from Africa and America.

Conclusions

This sociotechnical analysis identifies factors supporting and blocking the development of a global Super-grid. A main driver is the century old ideas that larger grids are more efficient and contribute to cooperation and peace. Over the last decades, the level of technical knowledge and networks of proponent have grown. The Super-grid also benefits from the potential opportunity of building on existing grids. Barriers stem from the scale of investments needed to experiment, path dependences in established industry and competition from novel smaller scale solutions based on local production, energy storage and smart grid technology. Other barriers originate in the organisational and institutional complexities of international electricity trade, and in the lack of trust at local and global levels, which hinder the development of institutions and required coordination.

An overarching conclusion from this analysis is that proponents of the Super-grid need to acknowledge the political reality of technical change. Technology is never apolitical, and the developments of large technical systems are always co-evolving with the political and the social. If the Super-grid is to be a part of the future, contribute to climate change mitigation and deliver on the promise to provide prosperity and empower the many, the discourse needs to open up, and move beyond ideals of 'optimisation', 'efficiency' and 'technocratic internationalism' and take a broader set of social benefits, risks and trade-offs seriously. To 'open up' the discourse can mean to invite other actors to the table, with the intent to remove barriers to a global Super-grid. It can also mean to re-assess the techno-economic framing, the goals and means suggested, even the value and necessity of this vision in the first place.

Appendix

See Fig. 2.

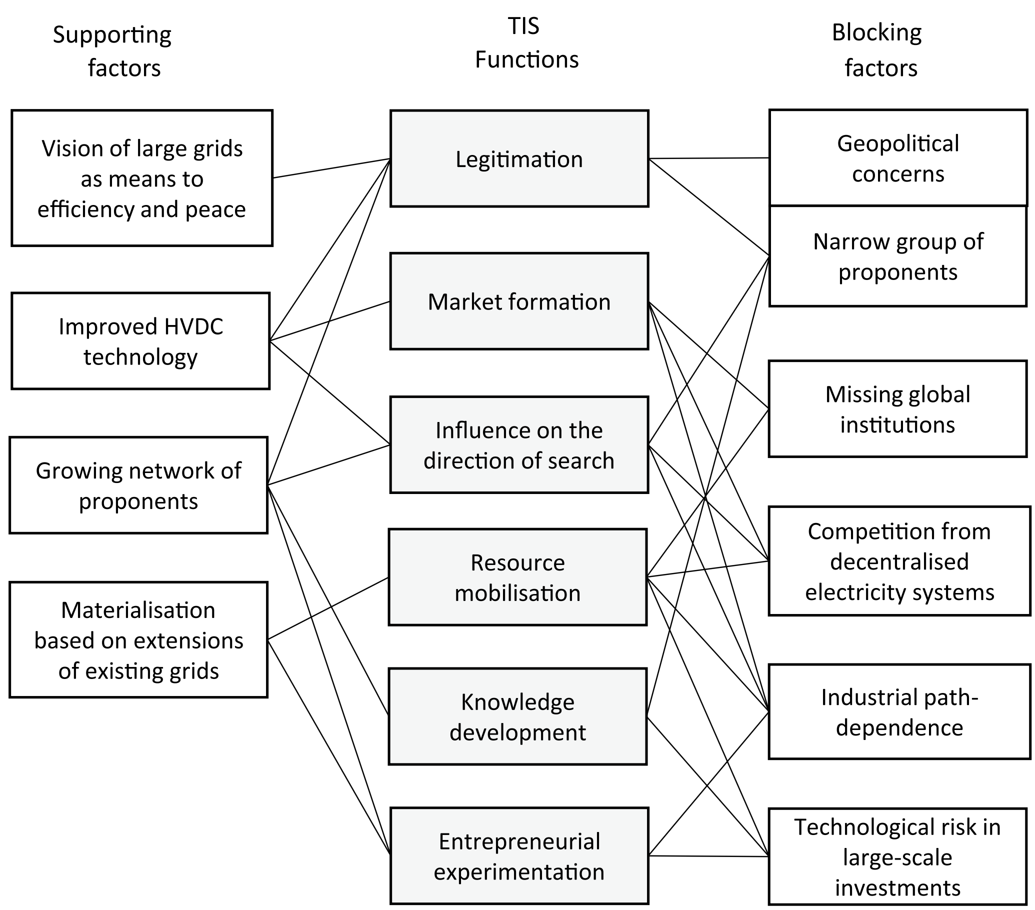

Fig. 2 Supporting and blocking factors derived from the heuristics of Technological Innovation System (TIS) functions. The supporting factors are counteracted by blocking factors. The different factors are discussed in separate sections of the paper. This snapshot picture does not visualise the feedback loops that would be part of a more dynamic model of system change (or lack thereof)

Abbreviations
TIS: Technological innovation system; HVDC: High voltage direct current; AC: Alternating current; VSC: Voltage source converter; TSO: Transmission system operator; EU: European Union; SGCC: State Grid Corporation of China; GEIDCO: Global Energy Interconnection Development and Cooperation Organization; CIGRE: International Council on Large Electric Systems.

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Author contributions
All three authors (KH, HA, BS) contributed to idea formulation. KH conducted the interviews and collected most of the data. The literature review was conducted by KH and HA. All three authors (KH, HA, BS) took turns in writing and rewriting the paper. All authors read and approved the final manuscript.

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Availability of data and materials
The study is based on openly available information and qualitative interview materials. Interview recordings are not anonymised and cannot be disclosed. Some data could be made available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Ethical approval not applicable. Interviewees have consented to contribute to the study.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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