A comprehensive review on the benefits and challenges of global power grids and intercontinental interconnectors

Maarten Brinkerink[a,b,*], Brian Ó Gallachóir[a,b], Paul Deane[a,b]

[a] MaREI Centre, Environmental Research Institute, University College Cork, Lee Road, Cork, Ireland
[b] School of Engineering, University College Cork, Cork, Ireland
[*] Corresponding author: maarten.brinkerink@ucc.ie

Keywords: Global power grid, Renewable energy, Variable renewables, Power transmission, Power systems modelling

Abstract: Globally interconnected power grids are proposed as a future concept to facilitate decarbonisation of the electricity system by enabling the harnessing and sharing of vast amounts of renewable energy. Areas with the highest potential for renewable energy are often far away from current load centres, which can be integrated through long-distance transmission interconnection. The concept builds on the proven benefits of transmission interconnection in mitigating the variability of renewable electricity sources such as wind and solar by import and export of electricity between neighbouring regions, as well as on other known benefits of power system integration. This paper reviews existing global and regional initiatives in context of a sustainable future and presents the associated benefits and challenges of globally interconnected power grids and intercontinental interconnectors. We find that while the challenges and opportunities are clearly qualified, actual quantification of costs, benefits and environmental implications of the global grid concept remains in its infancy, imposing a significant gap in the literature.

1. Introduction

The Paris climate change agreement sets a long-term goal of holding global average temperature increase to well below 2 degrees and pursuing efforts to limit this to 1.5 degrees above pre-industrial levels. Substantial research gaps in attaining the 1.5-degree target have been identified, including the ability of the energy system to transition to a zero-carbon system. Electricity is emissions free at its point of use and the decarbonisation of the power sector can enable decarbonisation elsewhere in the economy. Research on low carbon pathways to avoid dangerous climate change indicate a significant increase in global electrification [1–4]. It is not known whether this increase in electrification can be managed with the current infrastructure.

Many studies show the vast theoretical potential of renewable electricity (RES-E) for decarbonisation of the power system [5–7], yet the extent of practical implementation and reliability of such a system in the foreseeable future is a matter of debate due to the inherently variable nature in generation of core technologies such as solar-PV systems and wind turbines [8–11]. A valid approach to tackle the variability challenge is by interconnecting adjacent power systems to be able to import or export electricity during peaks and lows in generation [12]. Even more ambitious projects examine the extent to which interconnection between continental grids can be achieved.

The origin of the concept of globally interconnected power grids date back to the first half of the 20th century when inventor Buckminster Fuller considered the potential benefits of a global grid[1] with renewable energy (RES) as backbone, yet also dismissed the practicality at that time due to the limited maximum distances of power transmission (around 350 miles) [13]. Decades later, Buckminster Fuller presented a first representation of his concept of the global grid at the World Game Seminar in 1969, resulting in acknowledgement of the potential of the concept by the United Nations (UN) [14]. More recently at the 2015 UN Sustainable Development Summit in New York, Chinese president Xi Jinping announced that China will take the lead on discussions about establishing a 'global energy internet', to facilitate efforts to meet the global power demand with clean and green alternatives [15]. Furthermore, current UN Secretary General António Guterres considered the benefits of a global grid to be in line with UN's commitment to the 2030 Agenda for Sustainable Development and its objectives in regard to climate change [16]. Although there are some clear arguments supporting the concept of a global grid, implementation of intercontinental interconnectors to-date have been limited to short distance subsea AC links such as the Morocco-Spain and Egypt-Jordan interconnectors [17], and land-based interconnectors with limited flow between eastern Europe and central Asia.

This paper provides a comprehensive review, assessment and comparison of developments in- and research on global grids and intercontinental interconnectors as a potential pathway to future power system decarbonisation. To-date, no such overarching review exists within the scientific literature. Section 2 presents an assessment of the implications of grid integration of VRES and outlines to-date reviewed aspects of the global grid concept. Section 3 provides an overview of initiatives and compares projects and development trends related to the promotion or development of intercontinental interconnectors and the global grid concept. Section 4 provides an assessment of the arguments put forward in the literature supporting said developments, as well as potential risks and challenges. Section 5 incorporates an analysis of quantified results from performed techno-economic modelling studies in a global or intercontinental context. The review ends in section 6 where we discuss overarching research outcomes, limitations in the assessed literature and potential research gaps.

2. Review of previous literature

Historically, hydropower has been the most mature form of RES-E. Yet, throughout the last decade, new additions of both solar-PV and wind energy were underlined with impressive annual growth rates [18] showing an increase in global installed capacities of (on- and offshore) wind energy from 115 GW in 2008 to 514 GW in 2017 and 15 GW to 386 GW for solar-PV [19]. The inherently variable nature of solar-PV and wind energy in generation output and its impact on the electricity grid is a well-known challenge [8,9,12,20–22]. The dispatch of flexible generators can compensate for the variability up until a certain level of penetration of variable renewables (VRES). At higher penetration levels, especially when VRES displaces part of the dispatchable portfolio, this becomes a significant issue in terms of securing a match between demand and supply [8,9], as well as for maintaining stable inertia levels on the grid [10,11,23]. Despite these difficulties, a variety of continental- or global 100% renewable energy scenarios have been put forward [6,24–27]. Although these studies show the vast theoretical potential of RES-E for decarbonisation of the power system, the practical

[1] Within the literature a variety of terminology is applied such as Global Energy Interconnection (GEI), Global Energy Internet, Global Transnational Grid (GTG), global interconnected power grid and global grid for a similar concept. Throughout this article we refrain from using multiple terminologies and henceforth the term global grid will be used. The term intercontinental interconnectors will be used for transmission lines crossing continents.

implementation and reliability of such a system in the foreseeable future is often questioned [28,29]. To be able to decarbonize the electricity sector to contribute to overall emission reduction targets, while maintaining power system reliability, a variety of studies indicate the importance of a diverse and flexible low-carbon generation portfolio [11,22,30,31].

RES-E integration in the last decades has also emerged to decrease the dependency on import of fossil fuels from distant regions and to avoid its associated risks. As Robinson argues, "most countries favour renewables because they are indigenous resources" [32]. Following this analogy, the benefits of transitioning to a RES-E oriented power system with a focus on optimally utilizing local resources is being researched. Kaundinya and colleagues [33] conducted an extensive review on success and failure stories for standalone- and grid-connected decentralized (RES-E) power systems. Pleßmann et al. [34] assessed a global, decentralized 100% RES supply scenario with optimal combinations of solar-PV, concentrated solar power (CSP), wind energy and electricity storage for approximately 15.400 regions within 163 countries. This scenario, and similar power system scenarios depending on mostly storage technologies for balancing purposes (e.g. in [6,25,35]), can become viable in a situation where the availability and cost curve of storage technologies progresses significantly. Yet, to-date, an assessment of such scenarios fully depending on the availability of so far mostly unproven and costly storage technologies are often considered to "represent low probability outcomes" [28].

With growing penetration of VRES, an alternative or complementary approach to tackle the variability challenge is by interconnecting adjacent power systems to be able to import or export electricity during peaks and lows in generation. Historically speaking, transmission interconnectors were initially utilized to provide additional system security [32,36], after which the demand for cross-border trading, integration of wholesale electricity markets and these days the balancing of VRES have become core arguments for new transmission interconnectors [37]. Next to providing direct flexibility, interconnectors make the sharing of peak capacity possible [36], as well as the utilization of an overall more diverse, flexible and cost-efficient generation portfolio. The European Commission (EC) has underlined the importance of further market integration by endorsing a 10% interconnection target by 2020 (import capacity over installed generation capacity per member state) and 15% by 2030 for all member states [38]. Besides the earlier mentioned benefits, the expert group initiated to provide advise on how to make the 15% target operational [39], argues "that a fundamental role of transmission infrastructure is to enable the integration of areas of high renewable energy potential with main consumption areas". Assessing this remark from a global perspective, it becomes clear that there is a discrepancy between on the one hand main consumption areas and existing grid infrastructure, and on the other hand areas with the highest RES-E potential [5,7,23,36,40–42]. This observation is one of the core thoughts behind the concept of a globally interconnected power grid.

Certain specific aspects relevant to a global grid concept have been reviewed in detail. [17,43–50] provide an overview of the characteristics, trends and developments, prospects, reliability and commercial application of High Voltage Direct Current (HVDC) cables and convertors. Besides the former, [36] also reviews potential other required technologies for a global grid. Furthermore, [17] assesses the spatial implications, best practice of cable instalment, reliability and accident risks, and potential environmental issues for HVDC subsea power cable projects. Thomas and colleagues provide a review on the current research and prospects of superconducting transmission lines [51]. Engeland et al. [52] reviews the space-time variability of VRES generation from a regional to global perspective. Other reviewed aspects focus on the integration between backbone HVDC systems and smart grids [36,44,49], potential market models and development strategies [36,53–56], standardization needs for technologies in context of a global grid [36] and important treaties and laws for subsea HVDC cables [17]. Details of the elements assessed in these papers are therefore outside the scope of the current review. An assessment of previous literature demonstrates the availability of technical solutions such as HVDC cables, converters and laying equipment technology, but highlights a gap in the maturity of knowledge on the costs, benefits, challenges and opportunities of a global grid. The aim of this paper is to assess and compare these aspects to be able to determine the overall viability of the global grid concept as a means to global power system decarbonisation.

3. Initiatives and projects

3.1 Review and Comparison of Intercontinental interconnection projects

On a continental scale, Europe is on the forefront in terms of power system integration through transmission interconnection. Expansion outside the borders of the EU is an item of significant interest [57,58]. Feasibility studies conducted during the early 2000's on Trans-Mediterranean interconnectors, such as between Algeria-Spain or Algeria-Italy (direct or indirectly through Sardinia and the already existing SAPEI HVDC interconnector), indicated that financial feasibility is highly dependent on factors such as investment costs and sales prices of electricity [59]. The original 'Desertec' project proposed to supply between 700 TWh/yr [60] and roughly 1000

TWh/yr [61] of electricity generated by RES-E (mostly CSP) from the Middle-East and North-Africa (MENA) to Europe by 2050. The required investments of approximately 400 billion € [60] and the political unrest following the Arab spring revolution are often believed to be the downfall of the project [62] in its original form [63]. A similar project was The Medgrid Industrial Initiative which was formed in 2010 to support the design and promotion of a Mediterranean transmission network able to export 5 GW of electricity from MENA to Southern Europe [36,64]. This would be supported by 20 GW of mostly solar powered RES-E in MENA, with an overall estimated cost of the combined project between 38-46 billion € [64]. The MedGrid consortium ceased its operation in 2016 after completion of a number of planning and pre-feasibility studies [36].

Although projects on such scales to-date have not been pursued any further, smaller scale projects between Europe and MENA - and within MENA - are in order at different stages of development, gaining support from a range of regional initiatives and organizations (e.g. Friends of the Supergrid, Med-TSO and RES4MED). By receiving environmental approval from the Cypriot government late 2017 [65], the construction of the EuroAsia interconnector, interconnecting Greece (with Crete as intermediate landing point), Cyprus and Israel, can be commenced. Once completed, this 2GW, 1518 km long transmission link [66] will be the first (partial) subsea HVDC intercontinental interconnector and will reach maximum depths of around 3000 m. Moreover, the Cypriot, Greek and Egyptian governments agreed on a route for the 2 GW EuroAfrica HVDC interconnector [67]. The proposed route would cover 1707 km in total, with Cyprus and Crete as intermediate landing points. Italian transmission system operator (TSO) Terna is currently assessing plans for a 600 MW HVDC interconnector between Tunisia and Sicily [41,68]. Furthermore, Morocco and Portugal agreed on conducting a feasibility study for a 1 GW interconnector [41] and a 2 GW HVDC interconnector between Libya and Greece (with again Crete as intermediate landing point) is under consideration [69]. Other plans for interconnections between Northern-Africa and Europe are in earlier stages of development, such as prospects of the TuNur project combining the development of a 4.5 GW CSP project in the Tunisian part of the Sahara with three transmission pathways between Tunisia on the one hand and France, Italy and Malta on the other [70].

Next to the cross-Mediterranean subsea interconnection initiatives, a variety of land-based interconnection projects are in development to complete the so-called Mediterranean Ring (MedRing) of interconnected countries around the Mediterranean Sea [37]. Due to their advantageous geographical placement, Turkey is able to interconnect and synchronize their power system with Europe (synchronization with the European continental grid occurred in 2014) through AC links with Bulgaria and Greece, as well as towards Asia and the Middle-east [71]. Multiple existing- and planned AC- and back-to-back HVDC interconnections exist towards Armenia, Georgia, Iran, Iraq and Syria. Within the MENA region, Egypt is interconnected to Jordan with a 400 kV 450 MW AC subsea power cable crossing the red sea [17] and further plans have been made to reach a total transmission capacity of 2 GW between both countries [72]. Furthermore, a 3 GW HVDC interconnector linking Egypt and Saudi Arabia is expected to be operational by 2022, with an estimated total investment cost for the project of $1.56 billion [72]. This latter development could be the beginning of a pan-Arab power pool as envisioned by the Gulf Cooperation Council (GCC) [73].

One of the outcomes of the EU-Russia energy dialogue at the beginning of this decade was an "objective of moving towards a subcontinent wide interconnected electricity system and market" [74]. The possibility to utilize the vast renewable energy potential in Russia to partly supply the European market [36,75], introduced in the literature as the RUSTEC concept [76], would be an interesting option for further decarbonisation. Russia is currently interconnected to Finland with a 1 GW interconnector and with a number of smaller (below 200 MW) interconnectors to the Baltics and Norway. Yet, besides two additional small interconnectors towards Finland and Norway, concrete plans for further integration are not in sight. More than that, political unrest and conflicts in the region has led to a movement towards reduced dependency on energy from Russia [77,78].

In recent years, State Grid Corporation of China (SGCC) has been very active in pushing the integration of regional and intercontinental power grids as part of China's 'one belt, one road' initiative to export China's industrial overcapacity and engineering expertise [79]. Liu Zhenya, (now former) chairman of SGCC, stated that wind- and thermal power in the west of China can be produced and delivered to Germany at half of the current cost of locally produced electricity [80]. Following this concept, the Joint Research Centre (JRC) of the EC studied potential routes for a future power interconnection between China and the EU to inform policy makers, potentially by utilizing a multi-terminal setup integrating a range of European and Asian countries [81]. Figure 1 shows a simplified representation of these routes, as well as an overview of other existing, commissioned, considered and conceptually studied (see section 5) intercontinental interconnection projects.

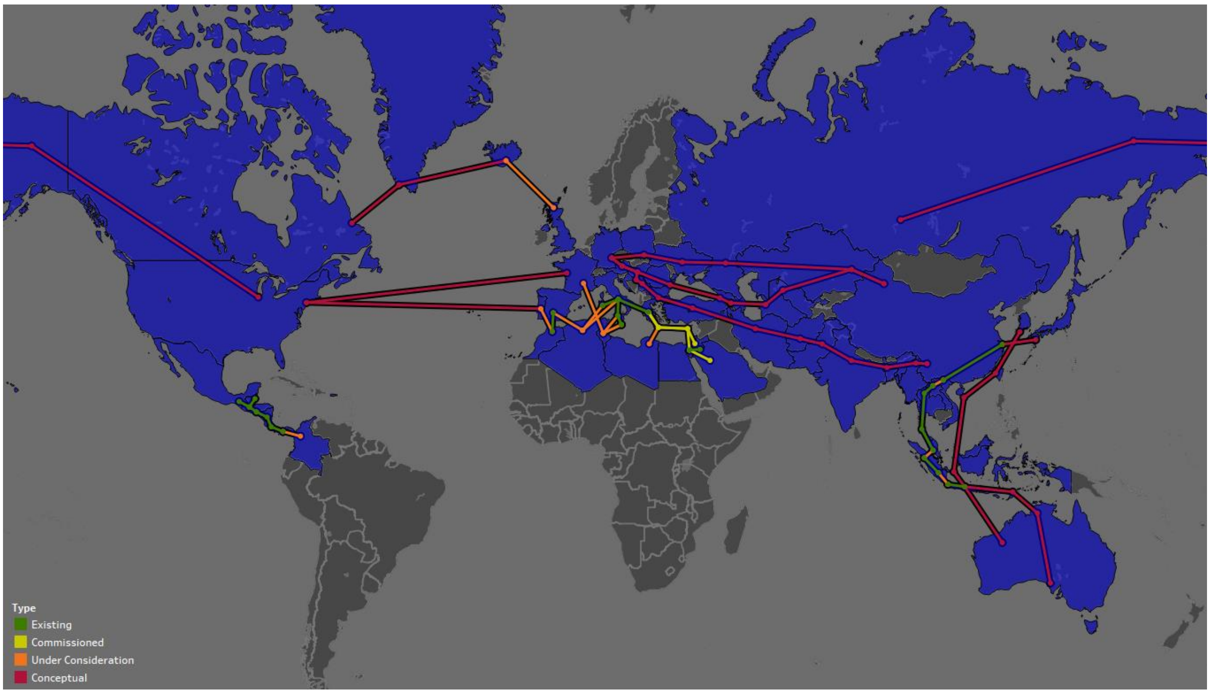

Figure 1 *Overview map of existing, commissioned, considered and conceptually studied intercontinental transmission pathways. Routes are indicative, they do not reflect accurate locational representation, nor do they show relative transmission capacities per pathway. Map includes intercontinental projects as described in this section as well as conceptually studied projects as mentioned in section 5. Continental supergrid projects (e.g. the Gobitec proposal) are not incorporated.*

On the western periphery of Europe, the development of the 1-1.2 GW, 1200 km long subsea HVDC Icelink interconnector, integrating the power systems of Iceland and Great Britain to utilize the high geothermal potential in Iceland, has been delayed. Although studies show the potential economic viability of such an interconnector depending on the setup of the business case [82,83], the progress in development is believed to be delayed by the 'Brexit' and fears of increasing electricity prices in Iceland [84]. Crossing the Atlantic by interconnecting Iceland and Greenland – or interconnecting Greenland and Canada – is currently deemed to be unrealistic by the relevant authorities despite the significant renewable energy potential [85]. Even more conceptual was an initiative in the early 90's to connect load centres in Russia and the United States (US) by bridging the Bering Strait with a 10,000 km long HVDC interconnector [86,87], yet this concept hasn't seen the light of day since then.

During the sixth summit of the Americas held by the Organization of American States (OAS, covering all 35 independent states in North- and South America) in 2012, the 'connecting the Americas 2022' initiative was endorsed. This includes the goal to achieve universal electricity access by 2022, among others by enhanced electrical interconnections throughout the Americas [88]. Currently, the six central American countries within the Central American Electrical Interconnection System (SIEPAC) are interconnected through a 300 MW backbone grid with plans for further expansion to 600 MW. The electricity markets of Belize and Mexico are expected to integrate with SIEPAC in the near future [89], as well as potentially Colombia after completion of the 400 MW HVDC interconnector towards Panama [41,90]. These ties link North- and South America, albeit with limited flow capacity to-date. Additionally, the interconnectivity expansion between countries in both continents stimulates trade between the Americas even more. For example, the US signed bilateral principles with Mexico in 2017 for further power system integration [91], as of early 2017 there are 11 pending applications for new Canada-US cross-border interconnectors [92] and additional cross-border interconnectors in South America are being commissioned [93–95].

The 'Gobitec' proposal was put forward in 2009, fuelled by the concept of the Desertec project, to interconnect the North-East Asia power grid (NEAG) by means of China, Japan, Mongolia and North- and South Korea [96]. Other NEAG advocates include Russia as well [97]. Following the Fukushima nuclear accident in 2011, the Renewable Energy Institute was initiated in Japan by the SoftBank Group to support the transition to renewables, among others by interconnecting the power systems of Asian countries [98]. The visualized Asian supergrid builds further on the NEAG concept, in addition to integrating India and the Association of Southeast Asian Nations (ASEAN). The vision of the institute is being backed by Korea Electric Power Company, SGCC and Russian power company PSJC Rossetti after signing a memorandum of understanding in 2016 [99]. According to the International Energy Agency (IEA), the developments towards an integrated ASEAN power system remain promising, yet challenging, due to a variety of natural and man-made obstacles [100]. Although these Asian super grid initiatives focus on grid integration on a continental level, it could enable and stimulate the flow of electricity between and throughout continents, for example towards Europe [80,81,101], or towards Australia by means of an ambitious prospect of integrating Australia with the Asian mainland through a subsea HVDC interconnector [102–104].

When comparing these projects, a number of trends and developments can be observed, namely; Due to the large capital investments, most projects require political support. Despite this, to-date, projects tend to fail due to costs, political unrest, lack of support or a combination of the above. Early concept projects tended to pursue large capacities of 5GW+ whereas more recent initiatives favour capacities in the range of 2GW reflecting the current standard of HVDC projects. The bulk of projects are land-based, but recently there has been a move to investigate subsea interconnections, exploiting advances made in this area. Overall, the idea of power system integration towards an (inter)continental scale is gaining significant traction.

3.2 Supporting Initiatives on the global grid concept

The Global Energy Network institute (GENI) was founded in 1986 to investigate the original global grid concept of Buckminster Fuller [105]. To-date, GENI's objective is to conduct research and inform the public and other relevant actors on the viability of interconnecting power systems between nations and continents.

In response to the 'one belt, one road' initiative and China's president Xi Jinping's vision of a global grid, SGCC initiated the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) in March 2016 [106]. Currently, over 200 universities and research institutes, energy enterprises and other entities are engaged in membership of GEIDCO [107]. Its purpose is to conduct research and promote the development of a global grid to meet the growing global demand for electricity in a sustainable fashion and to support the UN's agenda for sustainable development [108,109]. In 2017, GEIDCO signed a memorandum of understanding with multiple international organizations, including the United Nations Department of Economic and Social Affairs (UNDESA), to strengthen the cooperation for the purpose of sustainable development [110].

The Climate Parliament, an international cross-party network of legislators, initiated the Green Grid Initiative which among others supports the build of (inter)continental 'electricity highways' [111]. Compared to GENI and GEIDCO, this initiative utilizes a more top-down approach to create the political leadership- and will required to support the development towards a global green grid. To-date, ministers of 19 countries expressed their intention to participate (e.g. of Brazil, India, Indonesia and Mexico) as well as partnerships with among others the IEA and IRENA to provide technical advice. Similarly, under the umbrella of the Clean Energy Ministerial (CEM), discussions on the policy- and regulatory framework required for a global grid were undertaken [112].

While these support networks and organisations promote the idea of a global grid, there is still a lack of evidence on the concept to objectively inform policy development and decision-making and justify construction of any projects.

4. Benefits, opportunities, risks and challenges

Defining possible benefits, opportunities, risks and challenges of- and for intercontinental interconnectors and a global grid is of vital importance to support necessary decision-making for a future low-carbon power system and an overall sustainable future. The chart in figure 2 gives an initial overview of these aspects as mentioned within the literature, which will be discussed in more detail within this section.

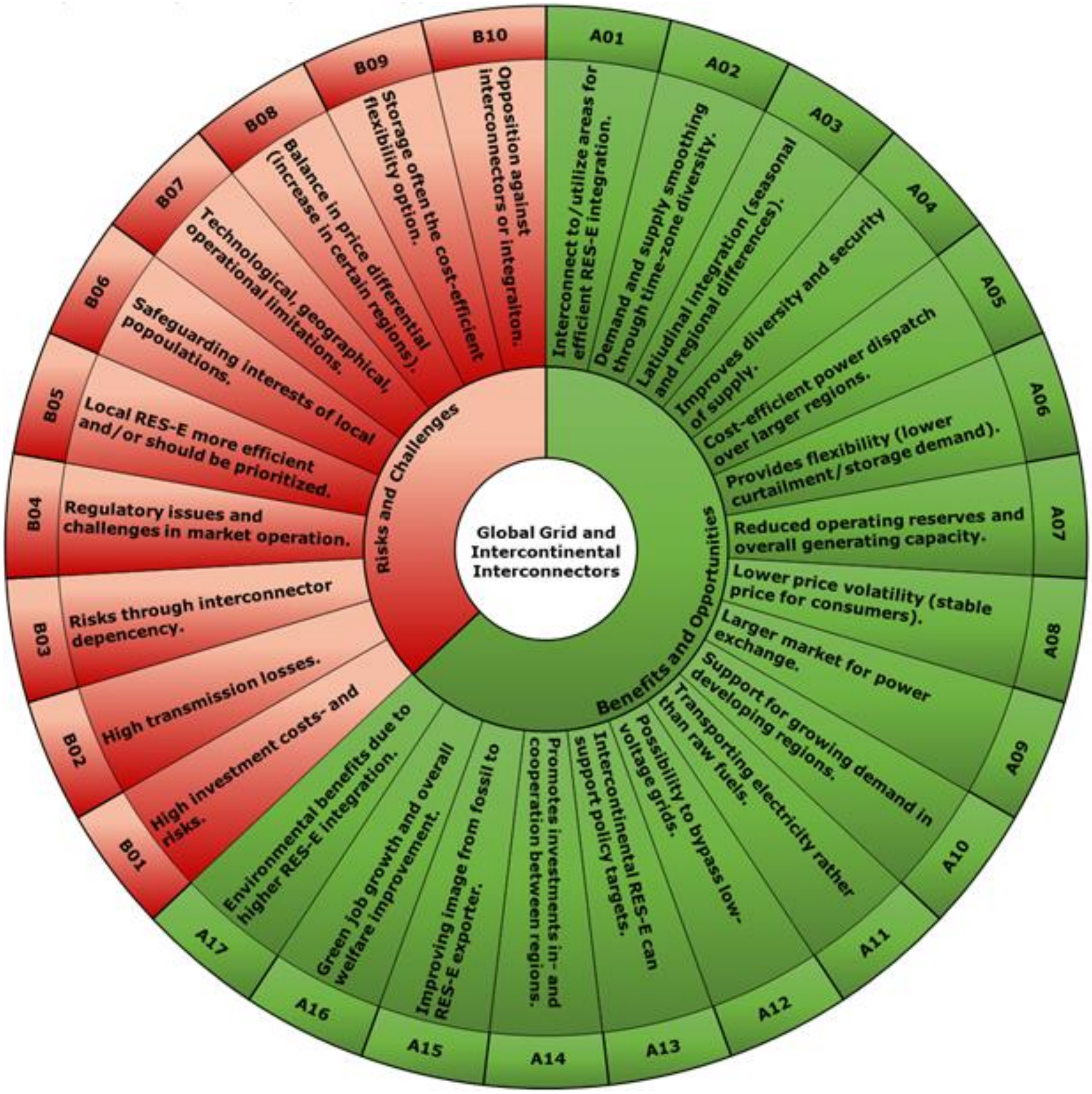

Figure 2 *Overview of mentioned benefits, opportunities, risks and challenges for a global grid and/or intercontinental interconnectors within the literature. The outer ring corresponds to further description of the benefits and opportunities (A) and risks and challenges (B) within this section.*

4.1 Benefits and opportunities

The discrepancy between on the one hand main consumption areas and existing grid infrastructure, and on the other hand areas with high renewable energy potential [5,7,23,36,40–42,113] is often regarded as a core argument for the benefits of a global grid. Considering the projected required RES-E capacities around the globe in line with the 1.5-2 degrees climate targets [3,4], utilizing the possibility to interconnect highly efficient-, unused- and sparsely populated regions for RES-E integration (A01), in parallel with optimizing the use of domestic RES-E resources, has gained significant interest. Czisch [114] indicates that in essence Europe has significant RES-E potential, yet the high population density could limit expansion towards higher RES-E penetration levels. Similar observations have been made for load centers in North-East Asia [96] and South-East Asia [102–104,115]. Norrga and Hesamzadeh [113] argue that next to the siting of RES-E, the possibility to install vast capacities of nuclear power plants at unpopulated and safe locations can be an important driver for a global grid and decarbonisation of the power system, however the analysis doesn't consider public acceptability as a significant challenge. Areas with significant RES-E potential and low population density, potentially able to supply intercontinental markets as identified in the literature, are on the outskirts of Russia for the European and Asian market [76], parts of Central and North-East Asia (e.g. Kazakhstan, Mongolia and Western China) for Europe, North- and South-East Asia [81,96,97,116–118], the Australian deserts for the South-East Asian market [42,48,102,103,115,117–120], MENA for the European market [41,60,61,73,114,121–124], Greenland for

Europe and North-America [125–127] and unpopulated regions in South-America for the Central and North-American markets [128]. While these studies focus on spatial availability, the consideration of geopolitical or public acceptance risks is often limited. For long-distance intercontinental interconnectors it is often argued to use a multi-terminal setup with connections to secondary lines. This allows transit regions to feed in RES-E or take out electricity as well, making optimal use of local resources [48,81,115,129]. However, such concepts would require detailed economic analysis.

The inherent variability in generation of VRES as well as the variability in locational demand can be smoothed by utilizing time-zone diversity through longitudinal power system integration with intercontinental interconnectors (A02, e.g. [81,126,130–133]). Ardelean and Minnebo [81] highlight the potential of a China-Europe transmission pathway by indicating that periods of high consumption on either side of the pathway often occur simultaneously with off-peak hours on the other side due to a time difference of seven hours. Furthermore, the authors show that solar output in Central Asia coincides with peaks in consumption in Europe or in China depending on the time of day, allowing for constant power exchange at peak electricity prices and an overall larger market for power exchange (A09). A similar strategy is envisioned by Chatzivasileiadis and colleagues [126] for RES-E export from Greenland to the European and North-American continents. Grossmann et al. indicate that by linking the main deserts in North- and South America the longest night (zero generation from solar-PV) can be reduced from 14 to 9 hours [128]. Conceptually, Kuwano [130] proposes to utilize the diurnal cycle of solar-PV generated electricity around the globe by linking significant solar-PV capacities with a global grid. Besides the importance of time-zone diversity, a range of studies [61,114,115,117,128,131,132,134] also indicate the potential benefits of the smoothing effect of area enlargement in VRES generation to an intercontinental scale. This is the case for longitudinal power system integration, but also for latitudinal integration by capturing seasonal and regional differences in load and VRES generation (A03). While utilizing time-zone diversity is a valid concept, it does necessitate longer interconnection distances for full exploitation. This increases the risk and complexity of such projects when compared to more local interconnections. Equally, the reviewed literature doesn't always account for future impacts of smart grid initiatives which also aim to smooth out local demand and supply, and therefore may dampen the benefit of time-zone diversity.

The ability to dispatch available low-cost generation capacity throughout larger regions by integrating continental markets can improve cost-efficiency in electricity generation (A05, e.g. [33,70,104,105,109, 116,118]). Besides cost savings during dispatch, integrating continental markets allows for the sharing of costly operating reserves and an overall reduction in required generating capacity (A07, e.g. [36,41,48,126,131,136]). Furthermore, intercontinental interconnectors can support the rapid growth of electricity demand in developing regions by utilizing existing generating capacity elsewhere (A10, [36,41,97,136]). In context of interconnecting the European and North-African power systems, a recent IEA report [41] argues that "interconnections are a viable option to ease the burden of North Africa's increasing demand: compared to investment in additional generation and operational costs, grid infrastructure is a low-cost solution. The structural overcapacity in Europe can help meet the North Africa's increasing need for energy." While such a concept has theoretical merit, it would be required to comply with existing European climate and energy regulations such as the European Emissions Trading Scheme (ETS) and European Renewable Energy Policy, complicating the operationality of such an idea. Grossmann and colleagues [128,137] indicate that when considering an interconnected Americas power system to be solely supplied by generation from solar-PV, the total capacity required is about equal to the capacity required for supplying the North-American continent alone based on purely domestic resources. Interconnections make the utilization of seasonal and diurnal differences in solar-PV generation possible, reducing the overall required capacity, as well as significantly reduce the demand for (costly) electricity storage (A06) compared to the original 'Solar Grand Plan' for the North-American continent [138]. However, these and similar studies do not include detailed reliability and adequacy assessments to demonstrate that this type of grid could be operated with the same level of reliability as today. Until successfully completed, such ideas remain conceptual.

The possibility to invest in regions with potential highly efficient RES-E resources promotes foreign investment in the RES-E industry in developing countries, which in turn can lead to further cooperation and commitment between regions (A14, e.g. [73,76,96,97,114,116,139,140]). Seliger and Kim [96] argue that the Gobitec proposal could be a catalyst for policy cooperation in the political tense region of North-East Asia. Grossmann and colleagues [128] highlight the significant role interconnections between the Americas could have on economic development in South America. Not only due to the expected revenue flows, but also in regard to an overall economic growth following the improved energy availability in the region. Other benefits and opportunities of intercontinental interconnectors and- or a global grid as mentioned within the literature are that it can improve diversity and security of supply (A04, e.g. [36,50,115,126,132,134]) and that it brings forth a lower price volatility in the interconnected regions resulting in an overall more stable price for consumers (A08, [36,61,126]). Boute and Willems [76] argue that the export of locally produced RES-E from biomass in Russia further into Europe might be a more cost-efficient and sustainable alternative to exporting the raw fuel itself (A11). A range of studies highlight the potential contribution intercontinental interconnectors and intercontinental

RES-E import could have on policy targets, such as the earlier mentioned decarbonisation- and interconnection targets within Europe (A13, [32,41,76,81,121,133]). Additional socio-economic benefits are the possibility to improve a country's image from fossil fuel exporter to RES-E supplier (A15, [76,102,103]), positive effects on green job growth [116,119,141] and an overall expected welfare improvement [97,133,141] (A16). Furthermore, significant environmental benefits are expected as a result of the higher RES-E integration and the decrease in electricity generation from fossil sources (A17, e.g. [36,40,60,97,134]). Bompard et al., [50] qualitatively benchmarks a global grid scenario to alternative decarbonization pathways and indicates that the concept could be particularly beneficial from an environmental viewpoint.

Lastly, some studies indicate that by directly interconnecting to areas with high RES-E potential, local low-voltage grids can by bypassed (A12, [37,126]). Yet, to-date, a core limit on RES-E integration lies within the weakness of local grids. Hence, although bypassing local grids might be an option in certain situations, for an optimally functioning intercontinental interconnector or possible (global) super grid it is essential that local transmission and distribution networks are able to support and distribute these bulk flows. Both in terms of Net Transfer Capacity (NTC) as well as coordination and exchange of information between transmission and distribution networks- and operators [23,37,45,49,142,143].

4.2 Challenges

Although the development of interconnections between countries and continents could enhance cooperation and economic development between regions as indicated earlier, it could also bring forth risks in case of supply dependency from non-domestic sources in often unstable regions (B03, e.g. [32,50,55,144–148]). An often made argument is that import of electricity from centralized distant regions has obvious similarities to the current dependency of large parts of the world on gas and oil imports from a set number of suppliers, including the risk of supply interruptions and its consequences [32,55,144,149,150]. Despite the similarities, there are also inherent differences, such as the fact that oil and gas can potentially be rerouted from different suppliers whereas electricity is dependent on fixed grids [144]. Next to that, gas and oil can be stored, allowing importers to store buffers, but more importantly, it allows suppliers to stop exporting without an immediate monetary loss on the long term [55,144]. Electricity needs to be consumed directly after generation, creating a different balance of power between supplier and consumer. Furthermore, unless a transmission line is physically disconnected, Kirchhoff's laws determine the flow of electricity [151], limiting the potential to alter supply directions. The vulnerability to supply interruptions in a Desertec scenario is assessed by Lilliestam and Ellenbeck [144]. They show that Europe in principle is not very susceptible to extortion following a potential export embargo from a single country. Only modest economic damage can be created, yet the exporting party might undermine its own market position in terms of direct income and long-term reputation. Only if all North-African countries combined would engage in an embargo Europe's vulnerability would increase [144]. Similarly, certain politically unstable countries such as North-Korea would significantly benefit from linkage into an Asian supergrid due to their poor power status [147], making it unlikely to engage in activities affecting the exchange of electricity. Czisch and Giebel [149] furthermore indicate that the amount of partners involved in a RES-E supergrid is much higher compared to the current relative monopolies in fossil fuel supply (e.g. OPEC countries), securing a higher intrinsically stable and diverse system. However, many investors are risk adverse and previous literature shows that political support and backing would be required for such projects. Overall, it can be argued that the N-1 contingency criteria for countries utilizing intercontinental interconnectors is of vital importance to limit the associated risks [96,97,144]. This can either be through interconnectivity with other regions or by securing sufficient domestic supply potential.

Utilizing potential resources in areas with high RES-E potential might be an attractive means to fuel decarbonisation, yet a stream of research highlights a competing development trend towards prioritization of decentral RES-E (B05). Certain studies advocate that it is deemed to be the cost-efficient solution [104,152–155] whereas others argue the societal preference for making use of indigenous resources [32,150]. Another societal concern is that by utilizing distant RES-E for import purposes, a 'sell-out' of local resources might occur which could otherwise be used for the domestic market (B06, [76,153]). Although this is a viable concern, it has also been indicated earlier that areas with some of the highest renewable energy potential are also areas with very low population density. That said, it is vital that expected trends in population growth, such as in Northern- [41,60] and Sub-Saharan Africa [156], are taken into account. Vice versa, by importing distant RES-E rather than making use of domestic resources, the economic- and employment opportunities that energy projects bring along are partly being lost to the exporting regions [76]. When it comes to providing flexibility for the variability of VRES, it is often argued that energy storage solutions in parallel with decentral VRES is a more economically viable solution (B09, [25,35,145]). However, because of the absence of detailed modelling of a global grid, as we'll discuss in more detail in section 5, such a statement cannot be verified. Despite that, storage could provide auxiliary services required for a functioning global grid [23] and although storage and interconnectors may often compete for similar roles [12], they can also reinforce each other by optimizing the utilization rate of interconnectors [23,115,119,157]. Again, the role of storage in a future global grid is poorly understood and requires research for greater insight.

A challenge for any transmission project, especially for long-distance and often sub-sea interconnectors, are the high investment costs- and risks associated with projects of this magnitude (B01, [17,32,36,58,80, 103,153]). In the past, and arguably so for the near future, it's been one of the core limiting factors on intercontinental interconnection projects [59,104]. Table 1 gives an overview of expected investment costs and transmission losses for intercontinental HVDC interconnectors as mentioned within the literature. Furthermore, costs of a range of to-date installed- or planned subsea HVDC interconnectors have been included as an indication for the current state of the art.

Table 1 *Overview of normalized investment costs, conversion- and transmission losses for existing- and conceptual HVDC (intercontinental) transmission projects as mentioned within the literature.*

Ref.	Year study	Conceptual, Existing, Commissioned,	Pathway	Specifics line	Costs Land-based line (€ Billion /1000 km)	Costs Subsea line (€ Billion / 1000 km)	% line loss /1000 km[1]	Costs Converter pair (€ Billion)	% loss Converter pair	Project costs (€ Billion)[2]
[158]	-	Existing	BritNed	1 GW, +- 450 kV	-	-	-	-	-	0.6, 250 km subsea HVDC
[159]	-	Commissioned	EuroAsia	2 GW, 400 kV						2.65, 1518 km subsea HVDC
[160]	-	Existing	NordBalt	0.7 GW, +- 300 kV	-	0.675[3]	-	0.193[4]	-	0.463, 400 km subsea HVDC
[161]	-	Commissioned	NordLink	1.4 GW, 525 kV	-	1.488[3]	-	0.396	-	1.332, 516 km subsea HVDC
[17,162]	-	Existing	NorNed	0.7 GW, +- 450 kV	-		5% incl. conversion		5% incl. line losses	0.6, 580 km subsea HVDC
[161]	-	Commissioned	NorthSeaLink	1.4 GW, 500 kV	-	1.224[3]	-	0.409	-	1.299, 720 km subsea HVDC
[17]	-	Existing	SAPEI	1 GW, +- 500 kV	-	-	-	-	-	0.73, 435 km subsea HVDC
[114]	2008	Conceptual	Europe-MENA	5 GW	0.35	3.5	4	0.3	1.2	-
[61]	2012	Conceptual	Europe-MENA	3 GW[5]	1.98[6]	2.38[6]	1.6	0.43	1.4	-
[35]	2014	Conceptual	Europe-MENA	3 GW[5]	1.65[7]	1.65[7]	-	-	-	-
[60]	2007	Conceptual	Europe-MENA	5 GW	-	-	3.33	-	-	-
[126]	2013	Conceptual	Europe-Greenland-N. America	3 GW, 800 kV	-	1.15-1.8	3	0.6	1.2	-
[133]	2018	Conceptual	Europe-Greenland-N. America	4 GW, 640 kV	-	-	2.12	-	2	-
[82]	2010	Conceptual	Iceland-UK	1.2 GW	-	1.24	4.3	0.28	1	-
[81]	2017	Conceptual	China-Europe	-	1.8-2[8]	6-8[8]	-	0.7-0.8	-	-
[163]	2016	Conceptual	North-East Asia	3 GW[5]	1.49[6]	2.38[6]	1.6	0.43	1.4	-
[116]	2014	Conceptual	North-East Asia	10 GW, 1000 kV	-	-	1.63	-	2.1	-
[115]	2012	Conceptual	South-East Asia-Australia	5 GW, 800 kV	0.77[4,7]	0.77[4,7]	3	-	2.7	-
[119]	2017	Conceptual	South-East Asia-Australia	3 GW	0.64[4]	2.58[4]	-	0.86	-	-
[117]	2012	Conceptual	South-East Asia-Australia	-	-	-	3	-	-	-
[128]	2014	Conceptual	Americas	-	-	-	2-3	-	-	-
[132]	2004	Conceptual	Global	3 GW[5]	0.79[7]	0.79[7]	3	-	-	-
				Mean	1.196	1.646	2.757	0.465	1.625	
				Median	1.14	1.475	3	0.42	1.4	

[1] *At full rated power, lower losses at non-full load.*
[2] *Note that total project costs can be lower than combined line and converter costs. Line costs are normalized to billion €/1000 km.*
[3] *Line costs for to-date subsea interconnectors include line costs for land-based connections to converter stations.*
[4] *Applied exchange rate of €1-US$1.16379.*
[5] *3 GW used for conversion.*
[6] *Costs converted back from (NTC) with indicated 20% reserve margin* [61].
[7] *Averaged value for HVDC, no distinction between land-based and subsea interconnectors.*
[8] *Includes potential costs for high capacity HVDC interconnectors as currently commissioned in China (800-1100 kV, 10-12 GW).*

The table indicates a significant range in normalized investments costs per 1000 km of transmission distance. Expected line costs for land-based HVDC interconnectors range between 0.35-2 billion €/1000 km and (expected) line costs for subsea HVDC interconnectors between 0.675-8 billion €/1000 km. A multitude of factors influence the cost expectations, such as cable characteristics (e.g. setup, type, voltage and wattage), the geography of the route (e.g. flat, mountainous or subsea) [17,81,146] and recency of the study. Refer to Ardelean and Minnebo [17] for a detailed assessment of these factors for subsea HVDC interconnectors. The majority of normalized costs as indicated within the literature are above the investment costs of to-date realised projects due to the generally higher voltage and wattage per line and converter. Yet, taking this and technological learning curves into account, assessment of the existing literature indicates that there's a development trend of decreasing project costs for (intercontinental) long-distance HVDC transmission. Another visible trend is the growing interest of intercontinental projects in China and other parts of Asia, reflecting the growing economy in Asia and its resulting need for power.

The median, as included in the table to limit the influence of outliers, in mentioned transmission losses normalized/1000 km is 3%, which seems to be a common assumption in intercontinental interconnector studies. Losses for a converter pair are deemed to be around 1.4-1.6%. The significant transmission losses associated with the utilization of long-distance transmission lines can be seen as a limiting factor to the overall feasibility of potential intercontinental interconnection projects (B02, [32,81,117]).

Clearly, the high capital investments required for intercontinental interconnectors and the associated risks are an obstacle to be overcome. The BritNed and NorNed projects indicate that a merchant investment mechanism, where profit margins are determined based on the price differential between interconnected regions, can be successful for long distance HVDC transmission projects and that it might be a realistic option for future intercontinental interconnectors [55]. Yet, a merchant investment approach encounters significant limitations, such as the lack of transparency in long-term regulated planning, making it difficult to assess the viability of investments [41]. Furthermore, profits run on short-term spot- or day ahead markets and not so much on long-term contracts, adding uncertainty for investors [126]. Next to that, a significant part of the benefits of power system integration on an intercontinental scale, such as the reduction in RES-E curtailment [61], the strengthening of regional grid stability [41] and significant cost-reductions in electricity generation are not part of the remuneration for private interconnector investors. This can be considered as a lack of incentives for market players to make high capital investments in developments which provide system-level advantages [61]. Hence, it is often argued that interconnectors can be seen as a public good and that a regulated investment strategy could be anticipated [32,41,48,126]. Robinson [32] suggests that "interconnectors should be built as part of a multi-country planning process and that the costs and benefits of the interconnectors should be socialised – in other words, shared – according to a set of principles agreed in advance". Furthermore, Gellings [48] argues that a global tax on greenhouse gas emissions could be a financial incentive to shift to carbon-free energy and that once first segments of a global grid are in place, such a carbon tax would catalyse private funding for further power system integration and RES-E capacity expansion. While this argument work in theory, real world implementation of carbon taxes has been politically difficult. Whatever investment mechanism is used for intercontinental interconnectors and a global grid, the costs and benefits of any project need to be clearly defined. This aspect will be further assessed in section 5.

Regulatory issues and challenges in market operations (B04) in a global grid context, such as the difficulty of integrating different types of power markets, are potential obstacles which need to be tackled [32,42,50,55,126,133,148]. Al Asaad [73] indicates the potential for a pan-Arab power pool, yet also highlights the differences in power market structures within the different countries of the GCC, from partly competitive to state-owned. In context of a possible transatlantic interconnector between Europe and North-America, Purvins and colleagues [133] state that power exchange between both continents would be challenging due to often incomplete exchange of information in competitive bilateral trading. Furthermore, the to-date lack of carbon pricing in power markets in large parts of North-America relative to the European ETS would prevent a level playing field in the transatlantic context [164]. Allowing competition between non-harmonized countries and regions as in the examples above would affect the competitiveness of market participants and possibly create unfair situations. Defilla therefore argues for an existing or new supranational institution to be assigned to act as global regulating institution [148]. Similarly, Chatzivasileiadis and colleagues [55,126] anticipate the need for a global regulator to provide a forum for communication among interested parties, coordinate investments and ensure a global competitive market environment, but also expect the need for an independent global TSO with a similar role compared to current regional and national TSO's. The authors envision two potential market models for a global grid, a hierarchical one where the backbone DC grid is separated from the underlying AC grid, or a more horizontal model where every regional market participates as an individual player [126].

Another challenge is that by integrating power systems an improved balance in marginal electricity prices between regions will occur, and although this leads to an overall cost reduction, it also means that in certain regions the cost of electricity generation- and potentially the electricity prices for consumers will go up (B08, [36,117,133]). Besides that, concerns regarding energy sovereignty [104], influence of politics on protecting the domestic energy mix [32], resistance of market participants to new entries [32] and local resistance against interconnector development (NIMBY) [148] are all factors influencing occurrence of opposition against interconnector development or power system integration (B10). Defilla argues that local opposition is the most time-consuming and often limiting factor in interconnector development. Considering the larger range of parties involved in case of an intercontinental interconnector project, good governance and communication within all layers of involved actors is deemed to be essential [148].

The inexperience in long-distance interconnection projects, especially when considering subsea pathways, causes uncertainties in regard to the impact of the local environment, geography and terrain on the feasibility of the project (B07, [17,37,59,81,103,146]). Walter and Bosch indicate that the most optimal transmission pathway is through flat barren lands and that it becomes significantly more expensive when considering occupied terrains such as agricultural areas or woodlands, sloped corridors or subsea sections. The calculated cost optimal-route for a conceptual interconnection between the east of Morocco and Paris does therefore not run upwards through Spain, but through the Mediterranean and the Italian- and Swiss mainland, mostly due to the ability to bypass natural barriers such as mountains and rivers [146]. Ardelean and Minnebo [17] mention the importance of avoiding deep trenches and steep slopes while maintaining the shortest path possible when considering a subsea interconnection. Maximum depths expected to be feasible were set at 2000 metres about a decade ago [165] and although depths of above 1000 metres are only reached in the Mediterranean sea so far [17], the commissioned EuroAsia and EuroAfrica interconnectors will reach depths of near 3000 metres [66,67], expanding the technological boundaries. Refer to [17] for a more detailed review of environmental aspects influencing cable performance and factors affecting the physical implementation of subsea interconnection projects.

On operational aspects, the risk of propagation of disturbances becomes more prominent with enhanced interconnectivity [166–168], especially on the scale of a global grid. Using Back to Back (B2B) HVDC interconnectors to prevent propagation between interconnected AC grids can be a solution [168,169], albeit with significant costs due to the high investments required for HVDC interconnectors as indicated earlier in this section. A collaboration between eight institutions and universities in Europe and the US engaged in 2017 in a project called the 'Global RT-Super Lab' [168,170]. During a demo event, an HVDC transatlantic interconnector was simulated through cloud-based communication, interconnecting the transmission systems of Europe and the US represented by the locations of the collaborating institutions. Different components of the power system, such as an actual wind farm in the US, were integrated during the simulations. Main goal of the demo was to assess the robustness of the interconnection in terms of acting as a 'firewall' against the real-time propagation of disturbances between the interconnected AC grids on both side of the DC link. The results indicated that the dispersed assets can simultaneously solve a grid stability problem by making use of the interconnection [171].

Finally, according to the ENTSO-E, occurrence of inter-area oscillations [172] are a "major concern when enlargements of the [Continental European] system are studied or carried out" [173]. It is clear that this challenge becomes more difficult to tackle when considering power system integration towards a global scale. Within Europe, Coreso has been appointed as a centralised regional security coordinator allowing the exchange of information between TSO's among others to help prevent significant disturbances to occur. A similar role could be assigned to a global institution such as the global regulator as introduced by Chatzivasileiadis and colleagues [55,126], or a separate independent institution.

5. Techno-Economic assessment

In the previous section we indicated the significant investments required for intercontinental interconnectors and a global grid. Yet, to be able to determine if these investments would be worth the capital and the associated risks, it's of vital importance that the net benefits are assessed and quantified while considering the full market impact [36]. Within this section we review and compare studies attempting to assess the techno-economic aspects of intercontinental interconnectors and the global grid.

5.1 Global grid

The first ever attempt to simulate the functionality of a global grid was done by Dekker and colleagues [174] in 1995. However, the complexity of the optimization problem and the available modelling software limited the practical implementation of the envisioned nine region global model at that time. Bompard et al., [50] benchmarks the global grid concept with alternative decarbonization pathways, yet does not include a quantified assessment of system-wide techno-economic effects. Albeit the limitations of this aspect are acknowledged in the study, the claim from the authors that the global grid option seems sustainable from an economic point of view remain unverifiable based on today's knowledge and literature.

Biberacher [132] performed a linear least-cost optimization solely based on optimal utilization of available solar-PV and wind energy potential for a global grid based on 11 nodes. The author indicates that in a scenario with sufficient availability of low-cost storage, global interconnectors are mostly used to compensate for recurring geographical discrepancies in demand and supply. Storage is deemed to be the cost-efficient solution in case of peak oversupply by storing the generated electricity locally. If storage is not available, global interconnectors are utilized to balance the short-term variability in generation as well, yet as Biberacher mentions; "the grid becomes massively oversized". Following the flow dynamics of the simulated global grid, a core flow of globally generated electricity towards load centers in South-East Asia and China can be identified, with Australia as main exporter.

In contrast, Aboumahboub and colleagues [131] used a optimization methodology for a global grid model consisting of 51 nodes of similar geographical size, disregarding current borders of power systems and associated generation portfolios. The results indicate that the overall required conventional backup capacity can be reduced by a factor eight when comparing the optimization of an interconnected- versus a non-interconnected scenario of the 51 regions. This shows the potential of utilizing seasonal and diurnal (time-zone differences) variability for smoothing of the global VRES generation. Similar to [132], the study showcases the importance of the duality between storage and global interconnectors. It furthermore indicates the cost-efficient RES-E import potential for China, India and South-East Asia in the global grid context. These findings are in line with the earlier described trend of growing interest in (intercontinental) interconnection projects in Asia due to its growing need for power. In a second study by the same authors [134], the potential of global carbon pricing was assessed in context of CO2 abatement targets. In a scenario where capacity expansion of interconnectors between the 51 regions is permitted, a shift can be seen in the cost-optimal solution from mostly biomass- and gas-based generation to increased levels of wind power penetration to reach the same abatement targets.

Ummel [40] applies a realistic limit on solar power capacity expansion while optimizing the deployment around the globe by restricting the global supply of solar powered electricity generation at 2000 TWh by 2030 (approximately 7% of 2030 global demand). The author indicates that "there is generally low correlation of optimal generating sites and the location of electricity consumption", which from an intercontinental perspective results in core power flows from MENA to Europe, the Persian-Gulf to India and from Australia to Indonesia. The modelling approach utilized in this study is restricted to the least-cost optimization of solar powered generation capacity. The supply of the remaining 93% of 2030 electricity demand is not incorporated in the simulations. In a similar study Bogdanov and Breyer [25] performed a linear optimization for a 2030 100% RES global energy system consisting of 23 regions across the globe. The authors highlight that the optimal solution is highly decentral, only 4% of energy demand is supplied by import of energy. Furthermore, besides a pathway interconnecting the Americas and a pathway interconnecting Southern Europe with MENA, the authors conclude that the results are a clear indication that a global grid does not generate benefits. Yet, the view of the authors that a 100% RES energy system (heat, power and transport) can be reached by 2030 seems optimistic.

A comparative assessment of these studies show some potential benefits of power system integration towards a global grid, however they contain a number of weaknesses which limits their value, namely; 1) the relatively low nodal representation [131,132,134,152,174], 2) low technological representation [40,132], 3) limited locational data representation (e.g. lack of input data based on actual locational load- or VRES profiles outside Europe) [40,131,132,152], 4) a focus on 100% RES-E modelling [131,132,152] and 5) the overall limited quantification of costs and benefits [25,40,50,174]. In a recent paper [164], we introduced a project aimed to fill this gap by developing a global interconnected power system model to assess the global grid concept with high technical and temporal resolution for a variety of future decarbonisation pathways. Furthermore, developments in open power system data [175–177] and computational power [178] can support improved assessments of the global grid concept.

5.2 Intercontinental interconnectors

Compared to studies assessing the global scale, studies focussing on the potential of separate intercontinental interconnectors or transmission pathways are more numerous and often supported by more detailed quantification. Brancucci and colleagues [121] indicate the potential for cost-efficient RES-E export from Northern-Africa to the European market. Although these findings are relevant within their respective scenario, being an EU power system largely based on coal and gas, the trend in continental Europe has evolved towards a more established RES-E portfolio. Potentially, a reversed flow could assist in transitioning the current fossil-fuel dominated power systems in Northern-Africa as well as support the growing demand for electricity [41]. Yet, as mentioned earlier, political instability in Northern-Africa has to-date limited the development of potential economically feasible interconnection projects due to uncertainty regarding the return on investments. Despite the uncertainty on transmission interconnection developments between Europe and MENA, studies assessing deep decarbonization of the 2050 Pan-European power system do highlight the cost-efficiency of utilizing the RES-E potential across the Mediterranean [61,114,179–181]. The E-Highway 2050 project, funded by the EC, showcases that in the higher RES-E scenarios approximately 10-40 GW of transmission capacity should be integrated between Northern-Africa and Italy, supporting the supply from up to 116 GW of installed solar capacity for demand centres in the European power market [179]. Overall, in a 2050 cost-optimal low-carbon combined energy system of Europe and MENA, Hess [182] identifies an empirical probability of technological integration of CSP export from MENA to EU through HVDC interconnectors of up to 66%.

Chatzivasileiadis and colleagues [126] assess the economics of a 3 GW transatlantic interconnector between Europe and North-America with intermediate landing points in Greenland and Iceland, while also incorporating a 3 GW offshore wind farm near Greenland with a capacity factor of 40%. The authors assume that electricity from the wind farm can always be sold at peak prices by utilizing time-zone diversity. The remaining capacity of the 3 GW interconnector can be used for power exchange between both continents. By assuming similar revenues compared to the NorNed project, the study indicates that the income for each delivered kWh would exceed 2-4 times the initial investments. In a follow-up study, the authors suggest that the amortization period for a direct link between the PJM interconnection (US) and Portugal is expected to be between 18-35 years [125]. Purvins and colleagues [133] simulate an interconnected European–North-American power system in a 2030 power dispatch model (North-America represented by a singular node). The results indicate that the majority of power exchange, being 27.4 TWh with a total capacity factor of 78%, through the 4 GW interconnector is directed towards North-America. The authors conclude that the overall socio-economic benefits for society, around 177 million €/year, are sufficient to cover the investment costs and hence that the project is welfare improving. Brinkerink et al. [164] confirms the potential for power exchange between Europe and North-America in an integrated 2050 power system model. Similarly to [133], the study identifies a general direction of flow towards North-America when considering standardized fuel and carbon pricing, mostly due to the higher relative RES-E penetration in Europe. Yet, the study also indicates the sensitivity of the combined merit order to integration of localized fuel and carbon pricing. This highlights the challenge of integrating different markets, as put forward in section 4.

Grossmann et al. [128] argues that considering expected solar electricity costs by 2030, and calculated costs of HVDC transmission for respectively interconnections between San Diego in the US and the Atacama- and Sechura deserts in South-America, solar electricity can be supplied for between 0.057-0.061 $c/kWh. This takes into account that 50% of installed capacity is based in South-America and 50% in the US, making optimal use of time-zone- and seasonal diversity in supply and demand. In an optimized 15 region 100% RES based 2030 energy system for Central- and South-America, Barbosa and colleagues [183] indicate that the overall cost can be reduced with 8.7% if transmission capacity expansion is part of the optimization. Yet, the overall flow of electricity between both continents is limited at 1 TWh. Continental generation in combination with significant storage capacities is deemed to be the cost-efficient solution.

In a similar study for the North-East Asian super grid context [163], the same authoring team showcases the significance of grid integration to make optimal use of available RES-E resources. Highly efficient wind power displaces decentralized solar-PV capacity. Mano et al. [116] indicate that a 100 GW RES-E project in the Gobi desert, including transmission pathways to China, Japan, North- and South-Korea, can be cost-efficient when a minimal capacity factor of 30% can be reached, which is feasible [184]. Zhenya and colleagues [97] argue in favour of a similar concept by highlighting that the average electricity price in Eastern China in 2016 was around $0.12/kWh, whereas the feed in tariff in Eastern Russia for RES-E is less than $0.05/kWh. In a cost-optimized 100% RES-E power system for Europe and China, Wu and Zhang [101] indicate that a transmission pathway between both regions could reduce annual investments by more than 30%.

The potential feasibility of Australian-(South-East) Asian interconnectors are underlined by a number of studies [115,117,119,120]. At today's prices and cost estimates, delivering solar electricity from Pilbara in Australia to Java can be delivered at an expected LCOE of $AUS 0.18-0.25/kWh [119]. Compared to the current feed-in tariff for solar electricity in Java at $AUS 0.193/kWh, the authors of the study argue that if present trends in cost reduction continue, the business case for this interconnector can be commercially viable within five to ten years. Blakers et al., [115] argues the importance of electricity storage to capture the midday solar-PV peak supply in Australia; the required capacity for an interconnector towards South-East Asian can be reduced with a factor four if peak generation- and flow can be smoothed out throughout the day. Contrary to the above studies, Gulagi et al. [155] concludes that the costs associated to the transmission of generated low-cost solar and wind electricity from Australia is too high compared to the option of regional generation and storage in South-East Asia.

Cova and colleagues [59] argued at the beginning of this century that financial feasibility of trans-Mediterranean interconnectors highly depends on factors such as investment costs and sales prices of electricity. Based on the analysis above, it is clear that almost two decades later the same conclusion is still valid for any intercontinental interconnection project. Although the benefits of intercontinental power system integration are obvious, the assessed studies show that actual feasibility strongly depends on among others the assumed required capex investments, assumed cost-reductions for technologies in future scenarios due to the technological learning curve and the contextual scenarios in which projects are assessed. More detailed power system modelling studies with high temporal, technical and spatial resolution, including sensitivity analyses, are a must.

6. Discussion

This paper provides a comprehensive review of the current literature related to the concept of a globally interconnected power grid. It reviews the benefits and challenges associated with a global grid- and with intercontinental interconnectors. It furthermore assesses existing initiatives supporting the concept, as well as an assessment of the state of the art of intercontinental interconnection projects.

The potential to utilize the vast quantities of efficient RES-E resources around the globe to decarbonize the global power system is significant. Among others, the possibility to smoothen demand and supply through area enlargement and time-zone diversity, as well as the discrepancy between consumption centres, existing grid infrastructure, and areas with high RES-E potential, could be valid reasons for power system integration towards a global grid and for the intercontinental exchange of electricity. Whether or not such a transformation to decarbonize the power system is worth the significant capital investments required is uncertain. A comparative assessment of literature and projects reveals that although the possible costs, benefits, challenges and opportunities of a global grid and intercontinental interconnectors are clearly qualified within the literature, actual quantification of costs and benefits remains in its infancy. Furthermore, to-date performed techno-economic modelling studies attempting to assess a global grid are often limited in their regional and technological representation and are mostly focused on 100% RES-E assessments. The limited quantification- and scope of these studies prohibits benchmarking of the concept to alternative pathways for decarbonisation of the global power system.

Key development trends related to the global grid concept include a decrease in costs for long-distance transmission technologies, in particular land-based and subsea HVDC, partly driven by China and other Asian countries as a result of their growing economies and consequential power demand. Furthermore, a transition towards projects pursuing the development of intercontinental interconnectors with overall lower transmission capacities as a result of failed overly ambitious projects in the past (e.g. Desertec) can be witnessed. Overall, initiatives supporting the global grid concept have been gaining traction in the last years [108,111,112].

Despite these initiatives, as Robinson [32] argues; "The case for the Global Grid rests on a fundamental geopolitical principle: that physical integration of world electricity grids will lower costs and make the world a safer place". As long as the detailed costs and benefits of global grids remain largely unquantified, it is inherently impossible to objectively inform policy development and decision-making, this being an essential factor for any large-scale transition to succeed. For future work [164], we aim to contribute to the filling of this gap in the literature by developing a global interconnected power system model with high technical and temporal resolution to assess the global grid concept for a variety of decarbonisation pathways and an overall sustainable future.

Acknowledgments

This work was supported by Energy Exemplar and Science Foundation Ireland (SFI) MaREI centre (12/RC/2302).

References

[1] Eurelectric. Decarbonization pathways; European economy; EU electrification and decarbonization scenario modelling; Synthesis of key findings. 2018.

[2] IEA. World Energy Outlook 2017. Paris: 2017. doi:10.1016/0301-4215(73)90024-4.

[3] McCollum DL, Zhou W, Bertram C, De Boer HS, Bosetti V, Busch S, et al. Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nat Energy 2018;3:589–99. doi:10.1038/s41560-018-0179-z.

[4] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, et al. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Glob. Warm. 1.5°C. An IPCC Spec. Rep. impacts Glob. Warm. 1.5°C above pre-industrial levels Relat. Glob. Greenh. gas Emiss. pathways, Context Strength. Glob. response to Threat Clim. Chang., 2018, p. 93–174.

[5] Deng YY, Haigh M, Pouwels W, Ramaekers L, Brandsma R, Schimschar S, et al. Quantifying a realistic, worldwide wind and solar electricity supply. Glob Environ Chang 2015;31:239–52. doi:10.1016/j.gloenvcha.2015.01.005.

[6] Jacobson MZ, Delucchi MA, Bauer ZAF, Goodman SC, Chapman WE, Cameron MA, et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. Joule 2017;1:108–21. doi:10.1016/j.joule.2017.07.005.

[7] Edenhofer O, Pichs Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, et al. Renewable Energy Sources and Climate Change Mitigation (Special Report of the Intergovernmental Panel on Climate Change). Cambridge: Cambridge University Press; 2012. doi:10.5860/CHOICE.49-6309.

[8] Denholm P, Margolis RM. Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. Energy Policy 2007;35:2852–61. doi:10.1016/j.enpol.2006.10.014.

[9] Pierre I, Bauer F, Blasko R, Dahlback N, Dumpelmann M, Kainurinne K, et al. Flexible generation:

Backing up renewables. Brussels: 2011.
[10] Ulbig A, Borsche TS, Andersson G. Impact of low rotational inertia on power system stability and operation. Proc. 19th World Congr. Int. Fed. Autom. Control Cape Town, South Africa. August 24-29, 2014, IFAC; 2014, p. 7290–7. doi:10.3182/20140824-6-ZA-1003.02615.
[11] Collins S, Deane JP, Ó Gallachóir B. Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model. Energy 2017;130:433–47. doi:10.1016/j.energy.2017.05.010.
[12] Brinkerink M, Shivakumar A. System dynamics within typical days of a high variable 2030 European power system. Energy Strateg Rev 2018;22. doi:10.1016/j.esr.2018.08.009.
[13] Fuller RB, Kuromiya K. Critical Path. St. Martin's Griffin; 1982.
[14] UN. Committee on natural resources, report on the 1st session, 22 February - 10 March 1971, Economic and Social official records, 50th session, supplement no.6. New York: 1971.
[15] UN. Towards Win-win Partnership for Sustainable Development; Remarks by H.E. Xi Jinping, President of the People's Republic of China. United Nations Sustain. Dev. Summit, New York, 26 Sept. 2015, 2015, p. 5.
[16] UN. Advancing the Sustainable Development Goals, António Guterres, United Nations Secretary General, UN; 2017.
[17] Ardelean M, Minnebo P. JRC technical reports; HVDC Submarine Power Cables in the World; State-of-the-Art Knowledge. 2015. doi:10.2790/95735.
[18] International Renewable Energy Agency (IRENA). REthinking Energy: Accelerating the global energy transformation. Abu Dhabi: 2017.
[19] International Renewable Energy Agency (IRENA). Renewable capacity statistics 2018. Abu Dhabi: 2018.
[20] de Boer HS, van Vuuren D. Representation of variable renewable energy sources in TIMER, an aggregated energy system simulation model. Energy Econ 2017;64:600–11. doi:10.1016/j.eneco.2016.12.006.
[21] Cochran J, Bird L, Heeter J, Arent DJ. Integrating Variable Renewable Energy in Electric Power Markets: Best Practices from International Experience, Summary for Policymakers. Golden, Colorado: 2012.
[22] Bertsch J, Growitsch C, Lorenczik S, Nagl S. Flexibility in Europe's power sector — An additional requirement or an automatic complement? Energy Econ 2016;53:118–31. doi:10.1016/j.eneco.2014.10.022.
[23] Guo B, Niu M, Lai X, Chen L. Application research on large-scale battery energy storage system under Global Energy Interconnection framework. Glob Energy Interconnect 2018;1:79–86.
[24] Jacobson MZ, Delucchi MA, Cameron MA, Frew BA. Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. Proc Natl Acad Sci 2015;112:15060–5. doi:10.1073/pnas.1510028112.
[25] Ram M, Bogdanov D, Aghahosseini A, Oyewo S, Gulagi A, Child M, et al. Global energy system based on 100% renewable energy - power sector. Lappeenranta: 2017.
[26] Connolly D, Lund H, Mathiesen B V. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016;60:1634–53. doi:10.1016/j.rser.2016.02.025.
[27] Fthenakis V, Mason JE, Zweibel K. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. Energy Policy 2009;37:387–99. doi:10.1016/j.enpol.2008.08.011.
[28] Heard BP, Brook BW, Wigley TML, Bradshaw CJA. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. Renew Sustain Energy Rev 2017;76:1122–33. doi:10.1016/j.rser.2017.03.114.
[29] Clack CTM, Qvist SA, Apt J, Bazilian M, Brandt AR, Caldeira K, et al. Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. Proc Natl Acad Sci 2017;114:6722–7. doi:10.1073/pnas.1610381114.
[30] Mileva A, Johnston J, Nelson JH, Kammen DM. Power system balancing for deep decarbonization of the electricity sector. Appl Energy 2016;162:1001–9. doi:10.1016/j.apenergy.2015.10.180.
[31] MacDonald AE, Clack CTM, Alexander A, Dunbar A, Wilczak J, Xie Y. Future cost-competitive electricity systems and their impact on US CO2 emissions. Nat Clim Chang 2016;6:526–31. doi:10.1038/nclimate2921.
[32] Robinson D. Economic and Geopolitical Determinants of Trade in Electricity. Int. Trade Sustain. Electr. Regul. Challenges Int. Econ. Law, Cambridge: Cambridge University Press; 2017, p. 54–73. doi:https://doi.org/10.1017/9781316681275.
[33] Kaundinya DP, Balachandra P, Ravindranath NH. Grid-connected versus stand-alone energy systems for decentralized power—A review of literature. Renew Sustain Energy Rev 2009;13:2041–50. doi:10.1016/j.rser.2009.02.002.
[34] Pleßmann G, Erdmann M, Hlusiak M, Breyer C. Global Energy Storage Demand for a 100% Renewable Electricity Supply. Energy Procedia 2014;46:22–31. doi:10.1016/j.egypro.2014.01.154.
[35] Bussar C, Moos M, Alvarez R, Wolf P, Thien T, Chen H, et al. Optimal allocation and capacity of energy storage systems in a future European power system with 100% renewable energy generation. Energy Procedia, vol. 46, The Authors; 2014, p. 40–7. doi:10.1016/j.egypro.2014.01.156.
[36] IEC. Global Energy Interconnection. Geneva: 2017. doi:978-2-8322-3680-2.
[37] Bompard E, Fulli G, Ardelean M, Masera M. It's a Bird, It's a Plane, It's a … Supergrid!; Evolution, Opportunities, and Critical Issues for Pan-European Transmission. IEEE Power Energy Mag 2014. doi:0.1109/MPE.2013.2294813.
[38] EC. COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL;

European Energy Security Strategy; {SWD(2014) 330 final}. Brussels: 2014. doi:10.1007/978-3-531-19201-7.
[39] EC. Towards a sustainable and integrated Europe; Report of the Commission Expert Group on electricity interconnection targets. Brussles: 2017.
[40] Ummel K. Global Prospects for Utility-Scale Solar Power : Toward Spatially Explicit Modeling of Renewable Energy Systems Working Paper 235 December 2010. 2010.
[41] IEA. Large-scale electricity interconnection - Technology and prospects for cross-regional networks. Paris: 2016.
[42] Zhenya L. Global Energy Interconnection. Elsevier Academic Press; 2015. doi:10.1016/B978-0-12-804405-6.00007-5.
[43] Chen G, Hao M, Xu Z, Vaughan A, Cao J, Wang H. Review of high voltage direct current cables. CSEE J Power Energy Syst 2015;1:9–21. doi:10.17775/CSEEJPES.2015.00015.
[44] Barnes M, Hertem D Van, Teeuwsen SP, Callavik M. HVDC Systems in Smart Grids. Proc IEEE 2017;105:2082–98. doi:10.1109/JPROC.2017.2672879.
[45] Kangwa N, Venugopal C, Davidson I. A Review of the Performance of VSC-HVDC and MTDC Systems. 2017 IEEE PES-IAS PowerAfrica, IEEE; 2017, p. 267–73.
[46] Qin X, Zeng P, Zhou Q, Dai Q, Chen J. Study on the Development and Reliability of HVDC Transmission Systems in China. 2016 IEEE Int. Conf. Power Syst. Technol., IEEE; 2016, p. 1–6.
[47] Sutton SJ, Lewin PL, Swingler SG. Review of global HVDC subsea cable projects and the application of sea electrodes. Int J Electr Power Energy Syst 2017;87:121–35. doi:10.1016/j.ijepes.2016.11.009.
[48] Gellings CW. A Globe-Spanning Supergrid. IEEE Spectr 2015.
[49] Rafique SF, Shen P, Wang Z, Rafique R, Iqbal T, Ijaz S, et al. Global Power Grid Interconnection for Sustainable Growth: Concept, Project and Research Direction. IET Gener Transm Distrib 2018;12:1–12. doi:10.1049/iet-gtd.2017.1536.
[50] Bompard E, Grosso D, Huang T, Profumo F, Lei X, Li D. World decarbonization through global electricity interconnections. Energies 2018;11:1–29. doi:10.3390/en11071746.
[51] Thomas H, Marian A, Chervyakov A, Stückrad S, Salmieri D, Rubbia C. Superconducting transmission lines - Sustainable electric energy transfer with higher public acceptance? Renew Sustain Energy Rev 2016;55:59–72. doi:10.1016/j.rser.2015.10.041.
[52] Engeland K, Borga M, Creutin JD, François B, Ramos MH, Vidal JP. Space-time variability of climate variables and intermittent renewable electricity production – A review. Renew Sustain Energy Rev 2017;79:600–17. doi:10.1016/j.rser.2017.05.046.
[53] Wang L, Gao Y, Zhou Y, Feng L, Guzman-Guemez J. Research on the future electricity market model for GEI based on the analysis of typical electricity market operation mechanisms. Glob Energy Interconnect 2018;1:197–208.
[54] Zhao Q, Liu G, Li Z, Liu D, Zhang L, Li H, et al. Simplified model of design of transnational and intercontinental electricity trading for Global Energy Interconnection. Glob Energy Interconnect 2018;1:209–16.
[55] Chatzivasileiadis S, Ernst D. The State of Play in Cross-Border Electricity Trade and the Challenges towards a Global Electricity Market Environment. Int. Trade Sustain. Electr. Regul. Challenges Int. Econ. Law, Cambridge; 2017, p. 21–45.
[56] GEIDCO. White Paper on Global Energy Interconnection; Development Strategy. Beijing: 2017.
[57] EC. EUROMED REPORT; MINISTERIAL DECLARATION BY THE EURO-MEDITERRANEAN ENERGY FORUM Rome, 1 and 2 December 2003. Rome: 2003.
[58] JRC. Transcontinental and global power grids 2018. https://ses.jrc.ec.europa.eu/transcontinental-and-global-power-grids (accessed November 18, 2017).
[59] Cova B, Pincella C, Simioli G, Stigliano GP, Vailati R, Zecca B. HVDC Interconnections in the Mediterranean Basin. Inaug. IEEE PES 2005 Conf. Expo. Africa, IEEE; 2006, p. 143–8.
[60] Trieb F, Müller-steinhagen H. Sustainable Electricity and Water for Europe, Middle East and North Africa. 2006.
[61] Zickfeld F, Wieland A, Blohmke J, Sohm M, Yousef A. 2050 Desert Power; Perspectives on a Sustainable Power System for EUMENA. 2012.
[62] Reuters. Germany's Bosch pulling out of Desertec renewable energy project 2012. http://www.reuters.com/article/bosch-desertec/germanys-bosch-pulling-out-of-desertec-renewable-energy-project-idUSL5E8MCI0T20121112 (accessed September 19, 2017).
[63] Desertec Foundation. Desertec Foundation is leaving the industrial consortium Dii 2013:1–2. http://www.desertec.org/press/press-releases/130701-desertec-foundation-is-leaving-the-industrial-consortium-dii/ (accessed September 19, 2017).
[64] EC. Medgrid - interconnecting the Mediterranean 2014. https://setis.ec.europa.eu/setis-reports/setis-magazine/smart-grids/medgrid-interconnecting-mediterranean (accessed January 3, 2018).
[65] EuroAsia Interconnector. EuroAsia Interconnector secures Cyprus government environmental approval 2017. http://www.euroasia-interconnector.com/news-euroasia_interconnector_secures_cyprus_government_environmental_approval1079period2017-12/?Period (accessed January 11, 2018).
[66] EuroAsia Interconnector. A Trans-European Energy Infrastructure Project; The EuroAsia Interconnector. 2017.
[67] EuroAfrica. EuroAfrica Interconnector final electricity cable route agreed between Cyprus and Egypt 2018. https://www.euroafrica-interconnector.com/euroafrica-interconnector-final-electricity-cable-route-agreed-between-cyprus-and-egypt/ (accessed June 20, 2018).
[68] TERNA. Piano di Sviluppo della Rete 2017 2016.
[69] ENTSO-E. Project 284 - LEG1 2016. https://docstore.entsoe.eu/Documents/TYNDP documents/TYNDP

2016/projects/P0284.pdf (accessed June 22, 2018).
[70] Neslen A. Huge Tunisian solar park hopes to provide Saharan power to Europe. Guard 2017. https://www.theguardian.com/environment/2017/sep/06/huge-tunisian-solar-park-hopes-to-provide-saharan-power-to-europe (accessed November 22, 2017).
[71] Saglam MA, Yilmaz M. Turkish electricity Network. Netw. Assess. Work. Athens, Greece, Athens: 2017.
[72] Farag M. Egypt becoming electricity hub between region, Europe: minister of electricity. Dly News Egypt 2018. https://dailynewsegypt.com/2018/02/06/egypt-becoming-electricity-hub-region-europe-minister-electricity/ (accessed June 20, 2018).
[73] Al-Asaad HK. Electricity Power Sector Reform in the GCC Region. Electr J 2009;22:58–64. doi:10.1016/j.tej.2009.08.013.
[74] EC and the Ministry of Energy of the Russian Federation. Roadmap EU-Russia Energy Cooperation until 2050. 2013.
[75] IRENA. REmap 2030 Renewable Energy Prospects for Russian Federation, Working Paper. Abu Dhabi: 2017.
[76] Boute A, Willems P. RUSTEC: Greening Europe's energy supply by developing Russia's renewable energy potential. Energy Policy 2012;51:618–29. doi:10.1016/j.enpol.2012.09.001.
[77] Reuters. EU to work with Baltic states on decoupling from Russian power grid 2017. https://www.reuters.com/article/baltics-energy-eu-russia/eu-to-work-with-baltic-states-on-decoupling-from-russian-power-grid-idUSL8N1IY455 (accessed February 7, 2018).
[78] Varfolomeyev O. Ukraine Moves to Integrate Its Power Grid With European Network. Eurasia Dly Monit Vol 14 Issue 91 2017. https://jamestown.org/program/ukraine-moves-integrate-power-grid-european-network/ (accessed February 7, 2018).
[79] Eric Ng. World power: Why China's State Grid is charged up over global interconnection dream. South China Morning Post 2016. http://www.scmp.com/business/china-business/article/1903687/world-power-why-chinas-state-grid-charged-over-global (accessed October 12, 2017).
[80] Hornby L. China looks to export surplus energy to Germany. Financ Times 2016. https://www.ft.com/content/68cdef50-f66a-11e5-803c-d27c7117d132 (accessed February 13, 2018).
[81] Ardelean M, Minnebo P. JRC science for policy report; A China-EU electricity transmission link; Assessment of potential countries and routes. Petten: 2017. doi:10.2760/67516.
[82] Hammons TJ, Hreinsson EB, Kacejko P. Proposed Iceland/UK (Peterhead) 1.2 GW HVDC cable. Univ. Power Eng. Conf. (UPEC), 2010 45th Int., 2010.
[83] Kvika and Poyry. Interconnector between Iceland and GB, cost benefit analysis and impact assessment; Presentation. London: 2016.
[84] Karagiannopoulos L. Iceland magma drilling project may revive giant UK power cable link. Reuters 2017. https://www.reuters.com/article/us-iceland-energy-britain/iceland-magma-drilling-project-may-revive-giant-uk-power-cable-link-idUSKBN17C17E (accessed June 21, 2018).
[85] Orkostofnun. North Atlantic Energy Network. Reykjavik: 2016.
[86] GENI. The Potential of an Electrical Interconnection Between Russia and North America 1992. http://www.geni.org/globalenergy/library/newsletters/1992/the-potential-of-an-electrical-interconnection-between-russia-and-north-america.shtml#Potential (accessed March 30, 2018).
[87] Belyaev LS. Rational use and efficiency of intercontinental electricity connections. Int J Glob Energy Issues, Spec Issue Cent East Eur Energy Policy 1994;6:268–74.
[88] OAS. MANDATES ARISING FROM THE SIXTH SUMMIT OF THE AMERICAS. Cartagena: 2012.
[89] IRENA. CLEAN ENERGY CORRIDOR OF CENTRAL AMERICA (CECCA) Strategy. 2015.
[90] BNamericas. Colombia-Panama interconnection line 2018. https://www.bnamericas.com/project-profile/en/linea-de-interconexion-electrica-colombia-panama-interconexion-colombia-panama (accessed June 22, 2018).
[91] Energy.gov. U.S. Energy Secretary and Mexico Energy Minister Sign Bilateral Principles to Promote Electricity Reliability of Interconnected Power Systems. DOEnews 2017. https://energy.gov/articles/us-energy-secretary-and-mexico-energy-minister-sign-bilateral-principles-promote (accessed December 22, 2017).
[92] Parfomak, Paul W.; Campbell, Richard J. & Pirog R, Ratner M, Brown P, Frittelli J, Humphries M. Cross-Border Energy Trade in North America: Present and Potential. Washington DC: 2017.
[93] Teixeira M. The Brazilian Energy Distribution System. TechinBrazil 2016. https://techinbrazil.com/the-brazilian-energy-distribution-system (accessed June 22, 2018).
[94] Casallas D. Andean interconnection plans take shape. BNamericas 2017. https://www.bnamericas.com/en/news/electricpower/andean-interconnection-plans-take-shape (accessed June 22, 2018).
[95] IADB. Peru and Chile Move Forward with Electrical Interconnection Project 2017. http://conexionintal.iadb.org/2017/08/02/peru-y-chile-avanzan-en-proyecto-de-interconexion-electrica/?lang=en (accessed June 22, 2018).
[96] Seliger B, Kim PG. Tackling climate change, increasing energy security, engaging North Korea and moving forward Northeast Asian integration – "Green Growth" in Korea and the Gobitec project. 2009.
[97] Zhenya L, Chen G, Guan X, Wang Q, He W. A concept discussion on northeast asia power grid interconnection. CSEE J Power Energy Syst 2016;2:87–93. doi:10.17775/CSEEJPES.2016.00053.
[98] Renewable Energy Institute. About "Asia Super Grid (ASG)" n.d. https://www.renewable-ei.org/en/asg/about/ (accessed March 30, 2018).
[99] Boyd J. Trio of Nations Aims to Hook Asia Super Grid to Grids of the World. IEEE Spectr 2016. https://spectrum.ieee.org/energywise/energy/the-smarter-grid/trio-of-nations-aim-to-hook-asia-super-grid-to-grids-of-the-world (accessed December 27, 2017).
[100] IEA. Development Prospects of the ASEAN Power Sector: Towards an Integrated Electricity Market.

2015.
[101] Wu C, Zhang X-P. Economic analysis of energy interconnection between Europe and China with 100% renewable energy generation. Glob Energy Interconnect 2018;1:529–36. doi:10.1417/j.2096-5117.gei.2018.05.001.
[102] Halawa E, James G, Shi X, Sari N, Nepal R. The Prospect for an Australian–Asian Power Grid: A Critical Appraisal. Energies 2018;11:200. doi:10.3390/en11010200.
[103] Mella S. Does Australia Energy Export Future Lie with the Asian Supergrid? Glob Energy Monit 2015;3:1–9.
[104] Blanch S, Law R, Campbell A, Halawa E, Eiritz C. Scoping workshop on Australia-South East Asia grid connection to catalyse regional generation and distribution of renewable energy. Darwin: 2013.
[105] Global Energy Network institute. About Us 2016. http://www.geni.org/globalenergy/about_us/index.shtml (accessed October 11, 2017).
[106] SGCC. Implementation of "The Belt and Road" Initiative - Promote China-Nepal Power Interconnection 2017.
[107] GEIDCO. List of members 2018. http://geidco.org/html/qqnyhlwen/col2017080782/column_2017080782_1.html (accessed June 28, 2018).
[108] GEIDCO. Overview 2018. http://geidco.org/html/qqnyhlwen/col2017080765/2017-09/23/20170923162727440712239_1.html (accessed June 28, 2018).
[109] GEIDCO. Global Energy Interconnection Action Plan to Promote the 2030 Agenda for Sustainable Development. Beijing: 2017.
[110] SGCC. GEIDCO Chairman Liu Zhenya Visits the Laos, Myanmar and Bangladesh Promoting Gird Interconnection 2017. http://www.sgcc.com.cn/ywlm/mediacenter/corporatenews/07/341836.shtml (accessed June 28, 2018).
[111] Climate Parliament. Green Grid Leadership Forum; Engineering a Climate Solution. Clim Parlimanet/LEGISLATORS Work Worldw TO Combat Clim Chang 2018.
[112] Clean Energy Ministerial. Regional and Global Energy Interconnection (RGEI) Initiative n.d. http://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/regional-and-global-energy-interconnection-rgei-initiative (accessed June 28, 2018).
[113] Norrga S, Hesamzadeh M. INTERGRID - Enabling a sustainable energy system by large-scale intercontinental power transmission. IEEE Power Energy Soc. Gen. Meet., 2013. doi:10.1109/PESMG.2013.6672688.
[114] Czisch G. Low Cost but Totally Renewable Electricity Supply for a Huge Supply Area - a European/Trans-European Example -. 4th Clavert. ENERGY Gr. Conf. – 24th to 26th Oct. 2008, Bath: 2008.
[115] Blakers A, Luther J, Nadolny A. Asia Pacific Super Grid – Solar electricity generation, storage and distribution. Green 2012;2:189–202. doi:10.1515/green-2012-0013.
[116] Mano S, Ovgor B, Samadov Z, Pudlik M, Jülich V, Sokolov D, et al. Gobitec and Asian Super Grid for renewable energies in Northeast Asia. 2014.
[117] Taggart S, James G, Dong Z, Russell C. The Future of Renewables Linked by a Transnational Asian Grid. Proc IEEE 2012;100:348–59. doi:10.1109/JPROC.2011.2159089.
[118] Grenatec. A "Pan-Asian Energy Infrastructure" By 2050. 2013.
[119] Mella S, James G, Chalmers K. Pre-feasibility study 2017; Evaluating the potential to export Pilbara solar resources to the proposed ASEAN grid via a subsea high voltage direct current interconnector. 2017.
[120] Wang C, Dargaville R, Jeppesen M. Power system decarbonisation with Global Energy Interconnection – a case study on the economic viability of international transmission network in Australasia. Glob Energy Interconnect 2018;1:507–19. doi:10.14171/j.2096-5117.gei.2018.04.011.
[121] Brancucci Martínez-Anido C, L'Abbate A, Migliavacca G, Calisti R, Soranno M, Fulli G, et al. Effects of North-African electricity import on the European and the Italian power systems: A techno-economic analysis. Electr Power Syst Res 2013;96:119–32. doi:10.1016/j.epsr.2012.11.001.
[122] Fulli G, Purvins A, L'Abbate A, Ruberg S, Migliavacca G. Evolutions and challenges towards a potential Pan-European HVAC / HVDC SuperGrid. CIGRE Int Symp 2011.
[123] Scholz Y. Renewable energy based electricity supply at low costs - Development of the REMix model and application for Europe. University of Stuttgart, 2012.
[124] Bogdanov D, Koskinen O, Aghahosseini A, Breyer C. Integrated renewable energy based power system for Europe, Eurasia and MENA regions. 2016 Int. Energy Sustain. Conf. IESC 2016, 2016. doi:10.1109/IESC.2016.7569508.
[125] Chatzivasileiadis S, Ernst D, Andersson G. Global Power Grids for Harnessing World Renewable Energy. Renew. Energy Integr., Elsevier; 2017, p. 161–74. doi:10.1016/B978-0-12-809592-8.00012-3.
[126] Chatzivasileiadis S, Ernst D, Andersson G. The Global Grid. Renew Energy 2013;57:372–83. doi:10.1016/j.renene.2013.01.032.
[127] Claverton Energy Research Group. Prospects for Trans-Atlantic Undersea Power Transmission 2010. https://claverton-energy.com/prospects-for-trans-atlantic-undersea-power-transmission.html (accessed January 14, 2018).
[128] Grossmann WD, Grossmann I, Steininger KW. Solar electricity generation across large geographic areas, Part II: A Pan-American energy system based on solar. Renew Sustain Energy Rev 2014;32:983–93. doi:10.1016/j.rser.2014.01.003.
[129] Purvins A, Wilkening H, Fulli G, Tzimas E, Celli G, Mocci S, et al. A European supergrid for renewable energy: Local impacts and far-reaching challenges. J Clean Prod 2011;19:1909–16. doi:10.1016/j.jclepro.2011.07.003.

[130] Kuwano Y. The PV Era is coming — the way to GENESIS. Sol Energy Mater Sol Cells 1994;34:27–39. doi:10.1016/0927-0248(94)90021-3.
[131] Aboumahboub T, Schaber K, Tzscheutschler P, Hamacher T. Optimization of the Utilization of Renewable Energy Sources in the Electricity Sector. EE'10 Proc. 5th IASME/WSEAS Int. Conf. Energy Environ., Wisconsin: World Scientific and Engineering Academy and Society (WSEAS); 2010, p. 196–204.
[132] Biberacher M. Modelling and optimisation of future energy system using spatial and temporal methods. Dissertation. University of Augsburg, 2004.
[133] Purvins A, Sereno L, Ardelean M, Covrig C-F, Efthimiadis T, Minnebo P. Submarine power cable between Europe and North America: A techno-economic analysis. J Clean Prod 2018. doi:10.1016/j.jclepro.2018.03.095.
[134] Aboumahboub T, Schaber K, Wagner U, Hamacher T. On the CO2 emissions of the global electricity supply sector and the influence of renewable power-modeling and optimization. Energy Policy 2012;42:297–314. doi:10.1016/j.enpol.2011.11.088.
[135] Nikolai Voropai, Sergei Podkovalnikov KO. From interconnections of local electric power systems to global energy interconnection. Glob Energy Interconnect 2018;1:4–10.
[136] Rudenko Y, Yershevich V. Is it possible and expedient to create a global energy network? Int J Glob Energy Issues 1991;3:1–10. doi:10.1504/IJGEI.1991.063683.
[137] Grossmann WD, Grossmann I, Steininger KW. Distributed solar electricity generation across large geographic areas, Part I: A method to optimize site selection, generation and storage. Renew Sustain Energy Rev 2013;25:831–43. doi:10.1016/j.rser.2012.08.018.
[138] Zweibel K, Mason J, Fthenakis V. A Solar Grand Plan. Sci Am 2008;298:64–73. doi:10.1038/scientificamerican0108-64.
[139] Shen H, Dai Q, Wu Q, Wu J, Zhou Q, Wang J, et al. The state-of-the-arts of the study on grid interconnection between Iberian Peninsula and West Maghreb region. Glob Energy Interconnect 2018;1:20–8. doi:10.14171/j.2096-5117.gei.2018.01.003.
[140] Komoto K, Enebish N, Song J. Very large scale PV systems for North-East Asia: Preliminary project proposals for VLS-PV in the mongolian gobi desert. 2013 IEEE 39th Photovolt. Spec. Conf., IEEE; 2013, p. 2376–9. doi:10.1109/PVSC.2013.6744952.
[141] Calzadilla A, Wiebelt M, Blohmke J, Klepper G. Desert Power 2050: Regional and sectoral impacts of renewable electricity production in Europe, the Middle East and North Africa. 2014.
[142] Nykamp S. Integrating Renewables in Distribution Grids : Storage, regulation and the interaction of different stakeholders in future grids. University of Twente, 2013. doi:10.3990/1.9789036500579.
[143] Verzijlbergh RA, De Vries LJ, Dijkema GPJ, Herder PM. Institutional challenges caused by the integration of renewable energy sources in the European electricity sector. Renew Sustain Energy Rev 2017;75:660–7. doi:10.1016/j.rser.2016.11.039.
[144] Lilliestam J, Ellenbeck S. Energy security and renewable electricity trade-Will Desertec make Europe vulnerable to the "energy weapon"? Energy Policy 2011;39:3380–91. doi:10.1016/j.enpol.2011.03.035.
[145] Koskinen O, Breyer C. Energy Storage in Global and Transcontinental Energy Scenarios: A Critical Review. Energy Procedia 2016;99:53–63. doi:10.1016/j.egypro.2016.10.097.
[146] Walter K, Bosch S. Intercontinental cross-linking of power supply - calculating an optimal power line corridor from North Africa to Central Europe. Energy Sustain Soc 2013;3:14. doi:10.1186/2192-0567-3-14.
[147] Song J. Super Grid in North - East Asia Through Renewable Energy. Tech Monit 2014:24–7.
[148] Defilla S. Good Governance for a Global Electricity Grid : What Are the Ingredients? Int. Trade Sustain. Electr. Regul. Challenges Int. Econ. Law, Cambridge University Press; 2017, p. 74–98. doi:https://doi.org/10.1017/9781316681275.006.
[149] Czisch G, Giebel G. Realisable Scenarios for a Future Electricity Supply based 100% on Renewable Energies. Energy Solut. Sustain. Dev., vol. no. 1608(E, Risø National Laboratory; 2007, p. 186–95.
[150] Elliott D. Emergence of European supergrids - Essay on strategy issues. Energy Strateg Rev 2013;1:171–3. doi:10.1016/j.esr.2012.04.001.
[151] Murillo-Sanchez CE, Zimmerman RD, Thomas RJ. Kirchhoff vs. competitive electricity markets: a few examples. 2001 IEEE Power Eng. Soc. Winter Meet. Conf. Proc. (Cat. No.01CH37194), IEEE; 2001, p. 1256–61. doi:10.1109/PESW.2001.917255.
[152] Bogdanov D, Breyer C. Global grid for 100% renewable energy supply. Conf. Proc. Dur. NEO-CARBON ENERGY 6th Res. Semin., Lappeenranta: 2016.
[153] Pearce F. Sunshine superpower; Is building a gigantic electricity plant in the Sahara really such a good idea. New Sci 2009;204:38–41. doi:10.1016/S0262-4079(09)62825-6.
[154] Hollain V. Kraftwerke in der Wüste: Ein Luftschloss auf Sand gebaut. SOLARZEITALTER 2009;1:74–7.
[155] Gulagi A, Bogdanov D, Fasihi M, Breyer C. Can Australia power the energy-hungry asia with renewable energy? Sustain 2017;9. doi:10.3390/su9020233.
[156] Barasa M, Bogdanov D, Oyewo AS, Breyer C. A Cost Optimal Resolution for Sub-Saharan Africa powered by 100% Renewables for Year 2030 Assumptions. 32nd Eur. Photovolt. Sol. Energy Conf. Exhib., Munich: 2016, p. 2570–611.
[157] Zhao L, Wang W, Zhu L, Liu Y, Dubios A. Economic analysis of solar energy development in North Africa. Glob Energy Interconnect 2018;1:53–62.
[158] 4coffshore. BritNed Interconnector 2018. https://www.4coffshore.com/transmission/interconnector-britned-icid19.html (accessed September 16, 2018).
[159] EC. EuroAsia Interconnector - Design, Implementation and Environmental Studies. Brussels: 2016.
[160] Reuters. UPDATE 1-ABB wins $580 mln Nordic-Baltic power order 2010.

https://uk.reuters.com/article/abb/update-1-abb-wins-580-mln-nordic-baltic-power-order-idUKLDE6BJ0Y520101220 (accessed September 16, 2018).
[161] Härtel P, Vrana TK, Hennig T, Bonin michael von, Wiggelinkhuizen edwin jan, Nieuwenhout frans d. j. Estimation of investment model cost parameters for VSC HVDC transmission infrastructure. Electr Power Syst Res 2017;160:99–108. doi:10.1016/j.epsr.2018.02.007.
[162] T&D World. NorNed, the Longest Electricity Cable in the World, is Operational. T&D World Mag 2008. https://www.tdworld.com/projects-progress/norned-longest-electricity-cable-world-operational (accessed September 16, 2018).
[163] Bogdanov D, Breyer C. North-East Asian Super Grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options. Energy Convers Manag 2016;112:176–90. doi:10.1016/j.enconman.2016.01.019.
[164] Brinkerink M, Deane P, Collins S, Gallachóir BÓ. Developing a global interconnected power system model. Glob Energy Interconnect 2018;1:330–43. doi:10.14171/j.2096-5117.gei.2018.03.004.
[165] Gevorgian V. Renewable Energy and Inter-island Power Transmission. CIEMADeS IV Int Conf 2011.
[166] Liu X, He J, Ding J, Yang M, Wang J, Tian C, et al. A Review on Research Methods of Disturbance Propagation in Large-Scale Power Grids. IOP Conf Ser Mater Sci Eng 2017;199:012112. doi:10.1088/1757-899X/199/1/012112.
[167] Pagnier L, Jacquod P. Disturbance propagation, inertia location and slow modes in large-scale high voltage power grids 2018:1–11.
[168] Bompard E. GLOBAL RT-SUPER LAB DEMO EVENT A real-time multisite co-simulation across the Atlantic for supporting Energy Transition. 7th IEEE Int. Conf. Innov. Smart Grid Technol., Idaho Falls, Turin: 2017.
[169] Setreus J, Bertling L. Introduction to HVDC Technology for Reliable Electrical Power Systems. Proc. 10th Int. Conf. Probab. Methods Appl. to Power Syst., IEEE; 2009.
[170] Mohanpurkar M, Hovsapian R, Suryanarayanan S. Real-time SuperLab. Fourth Int. Grid Simulator Test. Work. Natl. Renew. Energy Lab., Denver: 2017.
[171] Wagman D. Stress-Testing a Hypothetical Global Grid. IEEE Spectr 2017. https://spectrum.ieee.org/energywise/energy/the-smarter-grid/testing-the-systems-to-link-grids-across-continents (accessed October 14, 2017).
[172] Grebe E, Kabouris J, López Barba S, Sattinger W, Winter W. Low frequency oscillations in the interconnected system of Continental Europe. IEEE PES Gen Meet PES 2010 2010:1–7. doi:10.1109/PES.2010.5589932.
[173] ENTSO-E. Analysis of CE Inter-Area Oscillations of 1st December 2016. 2017.
[174] Dekker P-M, Meisen P, Bruton AB. THE GENI MODEL: The Interconnection of Global Power Resources to Obtain an Optimal Global Sustainable Energy Solution. Simulation 1995;64:244–53. doi:10.1177/003754979506400407.
[175] Liang X. Application and research of global grid database design based on geographic information. Glob Energy Interconnect 2018;1:87–95.
[176] Byers L, Friedrich J, Hennig R, Kressig A, Li X, Mccormick C, et al. A Global Database of Power Plants. 2018.
[177] EIA. International Energy Statistics 2018. https://www.eia.gov/beta/international/data/browser/ (accessed August 24, 2018).
[178] Sharma T, Glynn J, Panos E, Deane P, Gargiulo M, Rogan F, et al. High performance computing for energy system optimization models: Enhancing the energy policy tool kit. Energy Policy 2019;128:66–74. doi:10.1016/J.ENPOL.2018.12.055.
[179] E-Highway 2050. Europe's future secure and sustainable electricity infrastructure. 2015.
[180] Czisch G. Szenarien zur zukünftigen Stromversorgung; Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien. University of Kassel, 2005.
[181] Zickfeld F, Wieland A, Bartolot J, Sohm M, Neubarth J, Bardolet M. Desert Power : Getting Started. 2013.
[182] Hess D. The empirical probability of integrating CSP and its cost optimal configuration in a low carbon energy system of EUMENA. Sol Energy 2018;166:267–307. doi:10.1016/j.solener.2018.03.034.
[183] Barbosa L de SNS, Bogdanov D, Vainikka P, Breyer C. Hydro, wind and solar power as a base for a 100% renewable energy supply for South and Central America. PLoS One 2017;12. doi:10.1371/journal.pone.0173820.
[184] Komoto K, Ehara H, Lv F, Wang S, Sinha P, Cunow E, et al. Energy from the Desert: Very Large Scale PV Power Plants for Shifting to Renewable Energy Future. 2015.