

Connecting the Continents— A Global Power Grid

By Paul Deane and Maarten Brinkerink

THE DREAM OF A GLOBALLY CONNECTED POWER grid was once the stuff of science fiction. But today with powerful computer software, open data and international collaboration the concept of a global grid is moving one step closer to reality.

Globally interconnected power grids are proposed as a concept to facilitate the decarbonisation of world's energy system by harnessing and sharing vast amounts of clean renewable energy such as wind and solar. A challenge with renewables is that often the areas with the highest potential are far away from current load centres and this can be overcome 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.

The potential to utilize vast quantities of efficient renewable 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 renewable 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, 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% renewable assessments. The limited quantification and scope of these studies prohibits benchmarking of the concept to alternative pathways for decarbonisation of the global power system.

The idea of a globally interconnected power system actually dates back to the first half of the 20th century when inventor Buckminster Fuller considered the potential benefits of a global grid with renewable energy (RES) as backbone. The idea was dismissed at the time due to the limited maximum distances of power transmission (around 350 miles). However, decades later, Buckminster Fuller presented a first representation of his concept at the World Game Seminar in

1969, resulting in acknowledgement of the potential of the concept by the United Nations (UN). 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. Although there are some clear arguments supporting the concept of a global grid and indications that the idea is gathering international support, implementation of intercontinental interconnectors to-date have been limited to short distance subsea AC links.

Why a Global Power Grid?

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 by international scientists, 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 indicates that a significant increase in global electricity use is expected, however it is not known whether this increase in electrification can be managed with the current infrastructure.

While many studies show the vast theoretical potential of renewable electricity for decarbonisation of the power system, the extent of practical implementation and reliability of such a system is a matter of debate. A core challenge is dealing with the inherently variable nature of generation technologies such as solar-PV systems and wind turbines. A valid approach to tackle the variability challenge is by interconnecting adjacent power systems to share and balance variable resources. Electricity interconnectors are already playing an increasingly important role in the energy transition, as countries look to meet emissions and renewable penetration targets while maintaining energy security.

According to the International Energy Agency, the global capacity of high-voltage transmission links and interconnectors is approximately 250 GW. This is similar to the combined total generation capacity of France and Italy. The roll out of high voltage direct current (HVDC) grids was relatively modest in the 20th century, but in 2010 a significant leap forward was seen as the first ultra-high voltage (UHV) direct current project in China and the first offshore wind connection in Europe both came on line. A number of similar projects are planned and significant growth is expected to 2030.

On a continental scale, much of this activity is in Europe which is at the forefront in terms of power system integration through transmission interconnection. Connecting the European power system to regions outside of Europe is a topic of significant interest with feasibility studies undertaken on Trans-Mediterranean interconnectors, such as

between Algeria-Spain or Algeria-Italy. The well-publicized 'Desertec' project was a fore runner to many of these projects. The project proposed to supply approximately 800 TWh/yr electricity generated by renewable sources, mainly concentrated solar power from the Middle-East and North-Africa to Europe by 2050. The required investment of approximately 400 billion € was significant however and the future of the project became uncertain following political instability during the Arab spring revolution. Today projects of relatively smaller scale are being pursued.

On the western periphery of Europe, the development of the 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 also been delayed. Although studies show the potential economic viability of such an interconnector, the progress in development is believed to be delayed by the 'Brexit' and fears of increasing electricity prices in Iceland. More ambitious projects have also been explored including connecting the European and North American power systems by crossing the Atlantic to Iceland and interconnecting to Canada via Greenland. The concept is currently deemed to be unrealistic by the relevant authorities despite the significant renewable energy potential. Even more conceptual was an initiative in the early 90's to connect load centres in Russia and the United States by bridging the Bering Strait with a 10,000 km long HVDC, yet this concept hasn't seen the light of day since then.

Outside of Europe, there is significant activity in China. In response to the 'One Belt, One Road' initiative and China's president Xi Jinping's vision of a global grid, the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) was formed in March 2016. Currently, over 600 universities and research institutes, energy enterprises and other entities are engaged in membership of GEIDCO. 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. 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.

However, an obvious 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. In the past, and arguably so for the near future, it's been one of the core limiting factors on intercontinental interconnection projects. 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.

The table shows a significant range in normalized investments costs per 1000 km of transmission distance. Expected



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. Continental supergrid projects (e.g. the Gobitec proposal) are not incorporated.

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) and the geography of the route (e.g. flat, mountainous or subsea). 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.

On an individual project basic, high capital investments are a clear 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. 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. Added to this com-

plexity is the fact that a significant part of the benefits of power system integration on an intercontinental scale, such as the reduction in RES-E curtailment, the strengthening of regional grid stability 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 advantage. Hence, it is often argued that interconnectors can be seen as a public good and that a regulated investment strategy could be anticipated.

Across various studies, transmissions losses are estimated at 3% (normalized/1000 km, 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.

Benefits of a Global Grid

A core benefit of interconnecting continental grids is the ability to harness, share and manage large amount of variable renewable electricity. The discrepancy between main consumption areas and existing grid infrastructure on the one hand and areas with high renewable energy potential on the other is a core argument for the integration of a global grid. This becomes particularly important when looking to

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

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
-	Existing	BrittNed	1 GW, +- 450 kV	-	-	-	-	-	0.6, 250 km subsea HVDC
-	Commissioned	EuroAsia	2 GW, 400 kV	-	-	-	-	-	2.65, 1518 km subsea HVDC
-	Existing	NordBalt	0.7 GW, +- 300 kV	-	0.67 ⁵	-	0.193 ⁴	-	0.463, 400 km subsea HVDC
-	Commissioned	NordLink	1.4 GW, 525 kV	-	1.488 ³	-	0.396	-	1.332, 516 km subsea HVDC
-	Existing	NorNed	0.7 GW, +- 450 kV	-	-	5% incl. conversion	-	5% incl. line losses	0.6, 580 km subsea HVDC
-	Commissioned	NorthSeaLink	1.4 GW, 500 kV	-	1.224 ³	-	0.409	-	1.299, 720 km subsea HVDC
2008	Existing	SAPEI	1 GW, +- 500 kV	-	-	-	-	-	0.73, 435 km subsea HVDC
2008	Conceptual	Europe-MENA	5 GW	0.35	3.5	4	0.3	1.2	-
2012	Conceptual	Europe-MENA	3 GW ⁵	1.98 ⁶	2.38 ⁶	1.6	0.43	1.4	-
2014	Conceptual	Europe-MENA	3 GW ⁵	1.65 ⁷	1.65 ⁷	-	-	-	-
2007	Conceptual	Europe-MENA	5 GW	-	-	3.33	-	-	-
2013	Conceptual	Europe-Greenland-N. America	3 GW, 800 kV	-	1.15-1.8	3	0.6	1.2	-
2018	Conceptual	Europe-Greenland-N. America	4 GW, 640 kV	-	-	2.12	-	2	-
2010	Conceptual	Iceland-UK	1.2 GW	-	1.24	4.3	0.28	1	-
2017	Conceptual	China-Europe	-	1.8-2 ⁸	6-8 ⁸	-	0.7-0.8	-	-
2016	Conceptual	North-East Asia	3 GW ⁵	1.49 ⁶	2.38 ⁶	1.6	0.43	1.4	-
2014	Conceptual	North-East Asia	10 GW, 1000 kV	-	-	1.63	-	2.1	-
2012	Conceptual	South-East Asia-Australia	5 GW, 800 kV	0.77 ^{4,7}	0.77 ^{4,7}	3	-	2.7	-
2017	Conceptual	South-East Asia-Australia	3 GW	0.64 ⁴	2.58 ⁴	-	0.86	-	-
2012	Conceptual	South-East Asia-Australia	-	-	-	3	-	-	-
2014	Conceptual	Americas	-	-	-	2-3	-	-	-
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 normalization of values.

⁶ Costs converted back from (NTC) with indicated 20% reserve margin.

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 future and efforts required to meet the ambitious Paris Climate Change Agreement, which foresees a greater use of electricity throughout the economy and significant increase in wind and solar in global primary energy supply (from approximately 3% today up to 51% in 2050).

A number of studies have investigated the mismatch of renewable energy potential and population load centres. For example, Europe has significant renewable potential, yet the high population density could limit expansion towards higher renewable penetration levels. Similar observations have been made for load centres in North-East Asia and South-East Asia. Areas with significant renewable potential and low population density potentially able to supply intercontinental markets are typically in Northern and Sub-Saharan Africa and on the outskirts of Russia, Central and North-East Asia (e.g. Kazakhstan, Mongolia and Western China). The Australian deserts, unpopulated regions in South-America, Central and North-America have also been assessed for potential. While many of 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 HVDC setup with connections to secondary lines. This may allow transit regions to feed renewable energy in or take out electricity as well, making optimal use of local resources. However, such concepts would require detailed economic analysis. It is also argued that by directly interconnecting to areas with high renewable potential, local low-voltage grids can be bypassed. Yet, to-date, a core limit on renewable 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.

Core Challenges for a Global Grid

Although the development of interconnections between countries and continents could enhance cooperation and economic development between regions, it could also bring forth risks in case of supply dependency from non-domestic sources in often unstable regions. An often made argument is that importing 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. 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. 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. 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, limiting the potential to alter supply directions.

The vulnerability to supply interruptions in a Desertec scenario was assessed in the literature and it was shown that in principle Europe was not very susceptible to extortion following a potential export embargo from a single country. Only modest economic damage would be caused, yet the exporting party might undermine its own market position in terms of direct income and long-term reputation. However, the situation would be different if a supply interruption was coordinated with a number of countries. Similarly, certain politically unstable countries such as North-Korea would significantly benefit from linkage into an Asian supergrid due to their poor power status, making it unlikely to engage in activities affecting the exchange of electricity. However, this is with the assumption that all parties act economically rational, which in practice is often uncertain.

Regulatory issues and challenges in market operations are also a barrier to the global grid concept. For example, in context of a possible transatlantic interconnector between Europe and North-America, it is argued 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 Emissions Trading Scheme would prevent a level playing field in the transatlantic context. Allowing competition between non-harmonized countries and regions as in the example above would affect the competitiveness of market participants and possibly create unfair situations. Some argue that an existing or new supranational institution would need to be assigned to act as global regulating institution providing a forum for communication among interested parties, coordinate investments and ensure a global competitive market environment.

A development 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 may go up. Besides that, concerns regarding energy sovereignty, influence of politics on protecting the domestic energy mix, resistance of market participants to new entries and local resistance against interconnector development are all factors influencing occurrence of opposition against interconnector development or power system integration. Local opposition is often seen as 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.

The physical construction of long-distance interconnection projects is exposed to many uncertainties, especially when considering subsea pathways, local environment, geography and terrain on the feasibility of the project. Often the most optimal transmission pathway for overland lines is through flat barren lands and it becomes significantly more expensive when considering occupied terrains such as agricultural areas or woodlands, sloped corridors or subsea sections. For example, a study shows that 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. For subsea cables, avoiding deep trenches and steep slopes while maintaining the shortest path possible is a challenge. Maximum water depths expected to be feasible were set at 2000 metres about a decade ago and although depths of above 1000 metres are only reached in the Mediterranean Sea so far, the commissioned Euro-Asia and Euro-Africa interconnectors will reach depths of near 3000 metres, expanding the technological boundaries.

When comparing the pros and cons of HVDC and AC Power network for interconnection and global power grids, system faults and stability is a crucial issue for consideration. Many of these issues have been reviewed already by CIGRE in technical reports and publications. In general, faults causing significant voltage variation or power swings do not transmit across an HVDC lines. They may emerge on the

other end of an HVDC link as a reduction in power, without causing severe disturbances. In contrast to AC transmission, HVDC does not significantly increase the short circuit currents in both sending and receiving end of AC power networks. Another advantage of HVDC links in a global grid is that they do not suffer from the power angle stability problems which frequently occur with long AC transmission lines. Also, an AC transmission line is sensitive to disturbances of the power balance in AC power networks, and the power flow within AC lines is not easy to be controlled, whereas the controllability of an HVDC system can be used to support the stability of the connected AC networks by power runback or run-up. Furthermore, an HVDC link can provide additional benefits, like possible overload, reduced voltage operation. However, for a short time during a transient, an AC line may be able to transmit more power than a DC link, even beyond its steady state thermal capacity, while the transient overload allowed by the converter stations is usually smaller

Finally, a significant technical challenges need to be overcome to ensure the reliability of a possible global grid. According to the European Network of Transmission System Operators for Electricity (ENTSO-E), occurrence of inter-area oscillations in a synchronous grid are a “major concern when enlargements of the [Continental European] system are studied or carried out”. It is clear that this challenge becomes even more prominent when considering power system integration towards a global scale. Using HVDC interconnectors to prevent propagation between interconnected asynchronous AC grids can be a solution, albeit with significant costs due to the high investments required for HVDC interconnectors.

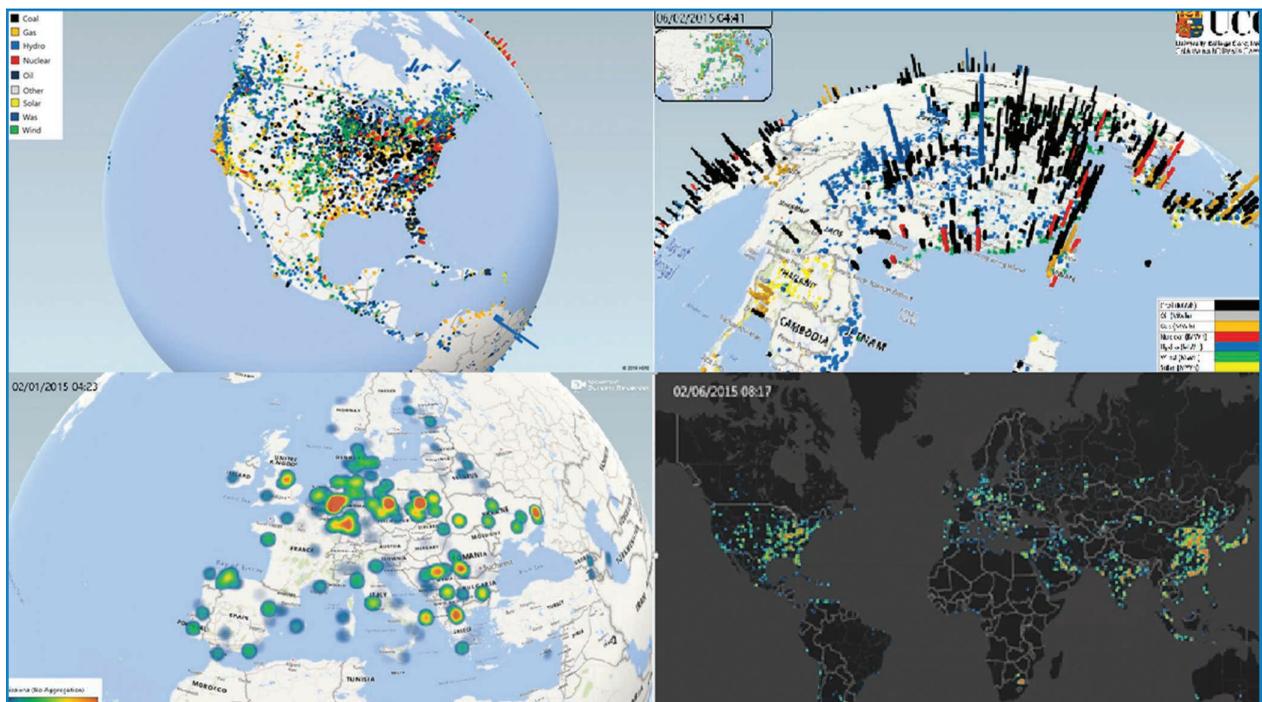


figure 2. Overview of PLEXOS World Global Model.

A collaboration between eight institutions and universities in Europe and the US engaged in 2017 in a project called the ‘Global RT-Super Lab’. 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. The 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 sides of the DC link. The results indicated that the dispersed assets can simultaneously solve a grid stability problem by making use of the interconnection. 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. Considering the superior number of parties involved in the operation of a global grid, a similar role could be assigned to a global institution to act as a global regulator.

Modelling a Global Grid

Being able to model and simulate a global grid is key to the initial understanding of its benefits and opportunities. The first ever attempt to simulate the functionality of a global grid was done by Dekker and colleagues 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.

Much more detailed analysis has been undertaken in 2019 by CIGRE- International Council on Large Electric Systems with a global electricity network feasibility study investigating the techno-economics of such a concept. The study demonstrated the potential of interconnection capacity between continental regions to enable massive wind and solar PV deployments that replace a significant share of fossil-based generation capacity. This translates into substantial increases of renewable shares in the electricity mix and drastic reductions of CO₂ emission levels. In terms of costs, the study shows that electricity mix shift towards variable renewable technologies sharply decreases the operational expenses of fossil based power plants, thus leading to overall system cost reductions from 54 to a minimum of 48 €/MWh. A number of sensitivity scenarios demonstrated that if a high carbon price can be agreed upon on a global level, the construction of interconnections allows to decrease both the cost of supplying global electricity demand as well as greenhouse gas emissions. Hence, as the number and size of interconnections keeps growing across the world, a global electricity grid may be envisaged as a valuable asset eventually connecting regions and continents to form a unique, cost-effective, low-carbon power system.

In more recent times, researchers at University College Cork have developed a detailed global electricity model allowing the hourly operation of most of the world power plants to

be understood. The model “*PLEXOS World*” [named after the software platform used] describes how the planets over 30,000 power plants operate over the year in over 164 countries. The tool brings together trends in big data, cloud computing and powerful software. The data is based on publicly available data from a small number of sources, particularly the World Resource Institute Global Power Plant Database. The model is fully developed in PLEXOS, which is a transparent energy modelling platform used by energy companies throughout the world and is free to academics for research.

The model gathers over 100 million data points from open databases around the world and uses parallel computing with Mixed Integer Programming to produce hourly results. The model uses a simplified representation of transmission and only net transfer capacities between regions are considered. The model will be used to undertake detailed studies of the global grid concept and in particular the implications for individual countries, with the objective to address the gap in knowledge on the techno-economic benefits of global grids.

Conclusion

The concept of a global grid, connecting continental power systems, is an exciting but uncertain prospect. 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. This is an active element of research we are engaged in at University College Cork together with international colleagues from universities and companies across the world.

While the idea of a global grid is incredibly ambitious, history has shown us that great endeavours are indeed possible and ideas once thought outrageous can come to pass. The idea of a global grid has a special historical relevance for researchers in Ireland looking at the issue. The first physical permanent link between continents was a communication cable from the southwest of Ireland (Valentia Island) to Newfoundland in July 1858. The Transatlantic Cable envisaged by the Cyrus Field was a huge undertaking. It required a cable twenty times longer than anything that had existed previously, it needed ships the size of which didn’t exist and required multi-million dollar investments to lay a cable at depths which had never been demonstrated. Above all it required new scientific endeavours and a belief in engineering and science to understand if a signal could be sent along such a long single piece of copper wire. The cable is a symbol for a scientific revolution that has changed the world. Time will tell whether global grids will have the same success.

Biographies

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