# Editorial: Towards 100% Renewable Energy System

THE penetration of variable renewable energy (VRE) resources (wind and solar Photovoltaic (PV)) is increasing rapidly across the world and in many regions by capacity is the dominant new generation that is connecting to the grid. This is part of an accelerating trend that dates back several decades. With this rapid increase in VRE there has been a trend in the popular press and in parts of the academic literature to claim that 100% renewables is not only a desirable end point but is relatively easily achievable – there is also a totally counter narrative that says you cannot possibly have a grid with very high penetrations of VRE and certainly not 100%. Neither of these narratives are useful or constructive. It is certainly technically possible to get to 100% VRE grids but is far from easy and certainly with our current technology and societal expectations around electricity it would be very expensive. A more balanced and correct statement would be "it is possible to get to 100% VRE grids but there are many challenges that need to be solved" and this is the subtext for this special section "Towards 100% Renewable Energy System".[1]

In the past number of years the trend towards ever increasing penetrations of VRE has led to many initiatives. In 2019 the Energy Systems Integration Group (ESIG) ran a workshop in Denver Colorado dedicated towards mapping out the research challenges of going towards 100% renewables (mainly VRE). This workshop was attended by over 60 experts mainly from North America and Europe with some small representation from other regions in the world. The output of this workshop was a report that can be downloaded at https://www.esig.energy/resources/toward-100-renewable-energy-pathways-key-research-needs/

Arising from this ESIG activity, the National Renewable Energy Laboratory (NREL) in collaboration with ESIG, Imperial College London, EPRI and several others established a core team and set about establishing the Global Power System Transformation Consortium (G-PST). The core team partnered with six system operators from around the globe. The chief executive officers of National Grid Electricity System Operator UK, California Independent System Operator (CAISO), Australia Energy Market Operator (AEMO), Ireland's System Operator (EirGrid), Electric Reliability Council of Texas (ERCOT), and Denmark's System Operator (Energinet) are champions in developing the consortium mission and activities. These system operators have one thing in common they all have high penetrations of VRE that are accelerating and they are all facing the associated planning and operating challenges. The G-PST seeks to solve these challenges in a collective manner and to disseminate the solutions globally to help others do likewise. Further details on the G-PST can be found at https://globalpst.org/

This special issue was conceived and developed in parallel with these and other initiatives. In the call for papers the topics of interest that were noted were very broad as this is in keeping with the challenges that arise. The challenges include power system dynamics that will be dramatically different in grids with very high penetrations of VRE that are connected to the grid through power electronics which are non – synchronous compared to the grids of the past that were completely dominated by synchronous generators. Of the 13 papers in this special issue the majority (seven) address issues in power system dynamics. It is interesting to note that in general most if not all the literature and/or public press that has fed the two sides of the debate around 100% renewables detailed above, do not address this important challenge in a meaningful way.

The first of two papers from Ireland's System Operator EirGrid, Qazi *et al.*, investigates the "Impact of Fault Ride Through Behaviour of Wind Farms on a Low Inertia System". Low inertia is a consequence of the non-synchronous nature of the state of the art wind and solar PV generators and it will be a common feature of all power systems in the future that have high VRE penetrations. Detailed analysis of real and reactive injections of fault ride through were used to identify technical scarcities and mitigations through novel system services are identified. The identification of scarcities and novel services to address them is a key feature of higher penetration of VRE.

The second paper from EirGrid, Madia *et al.*, also addresses a challenge brough on by low inertia, "Mitigating Extreme Over-Frequency Events using Dynamic Response from Wind Farms". An over frequency containment scheme that exploits the capability of VRE to provide protection and control resources is presented. Importantly this contribution addresses the ability of VRE to address the challenge highlighting an important point that VRE itself can provide many of the capabilities and services that arise with higher penetrations of VRE.

Another paper with system operator participation is from Switzerland with the Swiss system operator (Swisgrid) and academic colleagues from ETH in Zurich the US and Cyprus again tackle a low inertia issue, this time with a proposed novel controller for a Grid Forming inverter. Grid Forming inverters are clearly an emerging technology and show great promise in addressing many of the challenges that are being faced by system operators with increasing penetrations of VRE. This

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[1]It should be noted there are many other options for future clean grids including nuclear, hydro, geothermal, carbon capture and storage etc. but these are not the focus here.

is an area of enormous interest and activity and their paper Stanojev *et al.*, "MPC-Based Fast Frequency Control of Voltage Source Converters in Low Inertia Power Systems" is a very timely and clearly addressing a real challenge.

Cossart *et al.* from University of Lille, France tackle the very practical modelling issue that arises because synchronous machines have very different dynamic characteristics than the power electronic interfaces that are replacing them. Phasor based simulation tools in many instances are no longer adequate requiring time domain approaches that have a much higher computational burden. Cossart *et al.* in their paper "A Novel Event- and Non-Projection-Based Approximation Technique by State Residualisation for the Model Order Reduction of Power Systems with a High Renewable Energies Penetration" propose an approximation that reducing the computational burden and maintains accuracy. This highlights that despite the dramatic increase in computation capability it is still not capable of tackling the dimensionality of many of the challenges being faced as the penetration of VRE increases.

A Polish, Swedish and Spanish academic collaboration has contributed a paper that again addresses the inertia issue. Arredondo *et al.* in their paper "Stability Improvement of a Transmission Grid with High Share of Renewable Energy using TSCOPF and Inertia Emulation" they develop models of non-synchronous generation with synthetic inertia that can be used in transient stability constrained optimal power flow to arrive at safe and secure operating points. While the author's did not specifically address it, this paper along with others in this special section highlight that inertia is not a necessary condition for power systems of the future and this opens up the paradigm shift that is occurring as we go to higher penetration of VRE. To be explicit inertia is not a need but it is a service that addresses the most fundamental of needs, maintaining supply demand balance almost instantly, but this need can also be addressed by other services in this case emulation of inertia.

A paper from academia, and one industry collaborator, in Australia, Marzooghi *et al.,* "Scenario and Sensitivity Based Stability Analysis of High Renewable Future Grid" is a broadly based scenario driven stability study that is primed by a market simulation and load flow with sensitivities that also investigates the impact of system strength, prosumers and utility storage. The study while comprehensive uses simplified converter models and the authors rightly point to a potentially serious shortcoming i.e. ignoring converter driven instability which has been widely recognized as one of the new challenges for power system planning and operations as penetrations of VRE increase. These interactions are not only possible with VRE but with any converter connected device including storage, HVDC, some loads etc. This is not a criticism of this paper but rather a realization that there are so many moving parts in the energy system of the future that studies and analysis need to be focused to make them tractable but the results need to be interpreted in the light of the potential shortcomings.

The seventh and final paper that addresses power system dynamics by Holttinen *et al.* arises out of the very successful International Energy Agency, Wind Task 25 activity "Design and Operation of Energy Systems with high Penetration of Variable Generation". This highly successful activity has been going on for well over a decade and has evolved as the penetration of wind and more recently solar photovoltaic have increased. The paper "System Impact Studies for Near 100% Renewable Energy System Dominated by Inverter Based Variable Generation" has as would be expected a global list of authors from Finland, Ireland, USA, Denmark, Sweden, Norway, Portugal ranging from Industry to research institutes to academia. Similarly to the previous six papers this paper addresses the dynamics issue but also covers the other areas of importance including adequacy, flexibility, black start, protection etc. It also expands beyond electricity to look at sector coupling between transport, heating etc. and highlights gaps in our knowledge which are many, and makes some actionable recommendations. This paper marks a transition in the special section from dynamics and the system operator perspective as detailed in the G-PST to some broader issues. But before detailing these other contributions it is worth mentioning that there are a whole host of other challenges within the system operators area of responsibility that have not been addressed in this special section e.g. Control Room of the Future that will require significant improvements in our real time capabilities, tools, data, visualization and other topics such as defining and quantifying all the new services (not just those addressing the dynamics), new market designs etc. Further details on these can be found on the G-PST website (detailed above).

The paper by Härtel and Ghosh, "Modelling Heat Pump Systems in Low-Carbon Energy Systems with Significant Cross-Sectoral Integration" is clearly addressing the opportunities in sector coupling as VRE penetration increase, in this case between heat and electricity. This paper addresses the cross sector capacity expansion optimization problem with detailed modeling of heat pumps. Decarbonisation of heating is a big challenge globally and the debates that are ongoing as to the best way of achieving it are ubiquitous, complex and very localized. Heat pumps is clearly an electrification strategy mainly addressing domestic heating but there are economic, performance and system specific aspects (e.g. level of insulation in the housing stock) that make this a very complex area with multiple potential pathways. Good analysis illustrated in this paper is an important input for decision but decisions and action need to be taken at some stage with continuing analysis to guide the changes.

Optimisation as highlighted in the previous and other papers in the section is clearly a core enabler as we go towards 100% VRE and a paper by Yin and Wang of Southern Methodist University put forward a novel modelling framework that represents uncertainty in mid to long term planning that minimizes operational and investment costs. Their paper has a very clear title "Generation and Transmission Expansion Planning Towards a 100% Renewable Future" applies the modelling framework to a 100% renewables case study.

The last four papers in the section are focused on societal issues. Societal acceptance of infrastructure, adoption of technologies and/or communities desires for locally generated clean energy are all very significant drivers of the future energy system.

Engineers have a tendency to propose engineering solutions and assume that society should accept them. These four papers highlight the shortcoming of such an approach and through studies and methods illustrate the societal impact on going towards 100% VRE.

Schick *et al.*, from the University of Stuttgart study the "Role of Prosumers in a Sector-Integrated Energy System with High Renewable Shares". If as seems likely in many regions, the consumer (or prosumer if they are "producing" as well as consuming) is active in high VRE penetration energy systems through demand response, PV on their roofs, batteries, electric vehicles etc. they may form a significant resource in the energy system and cannot be ignored. This leads to very complex "central" versus "decentralised" architecture debate with a multitude of objectives and constraints. Traditionally the engineers with some help from economists would simply minimize the capital and operating cost of the entire system maintaining a policy directed level of reliability. Now the objectives of the prosumer also need to be included – a very difficult problem mathematically to formulate and solve and this paper is a good example of this emerging area.

A very international set of academic collaborators from Italy, The Netherlands, United States, Ireland and Sweden in their paper "Distributed Control of DC Grids: Integrating Prosumers' Motives" are at a high level tackling a similar problem as Schnick *et al.*. Cucuzzella *et al.* propose a control strategy for addressing a feasible, psycho-social-physical welfare problem in islanded DC grids. There are similarities with cyber physical systems which is a hot topic. Interestingly and very relevant is their focus on asymptotic convergence as we need to ensure that such systems are well behaved even with humans being in the loop.

Continuing the trend in this special section of international collaboration the paper by Price *et al.*, "The Implications of Landscape Visual Impact on Future Highly Renewable Power Systems: A Case Study for Great Britain" has academic authors from the United Kingdom, Germany, Denmark and Norway. The paper tackles the very real fact that visually many in society do not like looking at wind turbines and other VRE associated infrastructure including transmission. The authors find a significant cost difference (14%) when these factors are accounted for in their case study. Anecdotally this may be an under estimate considering the delays in developing large VRE projects and required transmission. These studies are valuable in putting real numbers on these societal factors which we need to consider carefully to actually deliver real tangible low cost solutions.

The final paper by Weinand *et al.* represents a German Danish academic collaboration aggregates the individuals into a municipality and considers the impact of their collective desire to be 100% renewable. It is well known that for VRE larger footprints are superior because of the smoothing and the access to greater range of flexibility. However, there are counter arguments for doing it all locally and this paper "Identification of Potential Off-grid Municipalities with 100% Renewable Energy Supply for Future Design of Power Grids" finds a feasible solution for a German case study and not surprisingly it is more expensive than to a more centralized minimum cost approach, however with security of supply concerns to the fore these types of futures may well develop.

In concluding this section has a diverse range of papers with a pocket of focus on power system dynamics which is reassuring to see as many of the non-power engineers in this drive to increase VRE and go towards 100% renewables are simply unaware of these important challenges. The papers are all timely and relevant to this important and increasingly important considering recent events. They are only scratching the surface in many respects considering the challenges that have to be overcome but with many others globally working on the same and/or similar topics solutions will emerge. Underpinning the global nature of the challenge, the global nature of many of the lists of authors in this section is a trend that will continue, hopefully with more industry involvement as the penetration level of VRE are increasing rapidly in real systems and the challenges are not purely academic. Finally, I would like to thank all my colleagues who helped in the review process, and both thank and apologies to the authors and the editors who tolerated my tardiness.

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