Guest Editorial

ENERGY Systems Integration (ESI) is the process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment. Energy systems have evolved from individual systems with little or no dependencies into a complex set of integrated systems at scales that include customers, cities, and regions. This evolution has been driven by political, economic, and environmental objectives. As we try to meet the globally recognized imperative to reduce carbon emissions through the deployment of large renewable energy capacities while also maintaining reliability and competitiveness, flexible energy systems are required. This flexibility can be attained through integrating various systems: by physically linking energy vectors, namely electricity, heat, and fuels; by coordinating these vectors across other infrastructures, namely water, data, and transport; by institutionally coordinating energy markets; and, spatially, by increasing market footprint with granularity all the way down to the customer level. Smart grids and ESI are related, in particular, the coupling between electricity, consumers, data and transport. This special section focuses on the aspects of ESI where electricity is coupled to water, heat and fuels and where this coupling brings challenges and/or opportunities.

The seven papers in this special section originate from Europe, Asia, North America and Australasia and several of the papers had multiple authors spread across the globe illustrating the international importance of ESI and the collaborations that have developed. The papers cover nearly the full range of ESI sub themes including the coupling between electricity with fuels, heat, gas; the coupling across scales and coupling with other infrastructures (e.g., water). Coupling between electricity and transport is a missing theme but not surprising considering the attention this topic has had in the past decade in the literature. Optimization at a planning and/or an operational time frame is central to nearly all the papers. The energy hub concept introduced over a decade ago by Geidl *et al.* at ETH Zurich features strongly in the literature survey sections of many of the papers, highlighting the importance of the concept.

Renewables integration is an important driver of ESI highlighted in nearly all the papers. The flexibility benefits of integrated energy systems are highlighted throughout by a set of case studies that range from small district heating systems to national scale systems. Enhanced reliability, economic benefits and reductions in emissions all feature strongly across the seven papers and all stem from the ESI approach.

A common theme within the papers is the modelling challenge that ESI problems present. The increased coupling between vectors, across scales, with the consequential network constraints, and in the context of variable renewables the increasing stochasticity all leads to extremely large dimensional problem formulations. These are overcome partially by various innovations in the seven papers including thoughtful assumptions, methodological contributions and the limited scale of the case studies. However, for real applications it is clear from the papers conclusions and indicated future work that these challenges are in need of significant research to resolve fully. Market design challenges did not feature strongly in the seven papers although real implementation, as pointed out in at least one of the papers, will require new and increasingly complex market designs. This highlights the importance of ESI not only as a concept of physical coupling and coordination but of institutional coupling and coordination, for example, governance and regulation need to be fully integrated if the physical benefits of ESI are to be realized.

Below is a brief description of each of the seven papers, a difficult task to summarize in a few sentences so I would encourage you to read them all in detail.

A China, USA collaboration has resulted in a paper by Liu *et al.*, *Operational Reliability Assessment for Gas Electric Integrated Feeders.* The energy hub concept is central to their contribution, the interactions of gas-electric energy can help reduce the power system outage risk especially in peak load periods.

Oikonomou and Parvania in their paper *Optimal Coordination of Water Distribution Energy Flexibility with Power Systems Operation*, explore the operational flexibility that coordination between electricity and water can unleash. This highlights the importance of ESI not only as an energy vector coordination strategy but as a beneficial coordination strategy with other infrastructures.

Yang *et al.* in their paper, *Modeling the Operation Mechanism of Combined P2G and Gas-Fired Plant With CO2 Recycling*, is one of several papers that explore the benefits of coupling across multiple energy vectors as a carbon reduction strategy. The proposed solution is to integrate multiple technologies into energy hub/multi-energy plant thus increasing efficiencies and minimizing emissions and interestingly there is an emphasis on a localized solution to avoid transportation across long distances highlighting the tradeoffs between the different aspects of ESI, i.e., coupling across energy vectors and/or across geographical scales.

A U.K., Australia contribution by Cesena and Mancarella, *Energy Systems Integration in Smart Districts: Robust Optimisation of Multi-Energy Flows in Integrated Electricity, Heat and Gas Networks*, invokes the energy hub concept with multiple energy vectors and tackles uncertainty in an

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operational time frame. Importantly this contribution addresses the network constraints which are so important in integrated energy systems.

Zhang *et al.* in their paper, *Whole-System Assessment of the Benefits of Integrated Electricity and Heat System*, address the planning problem for a national scale integrated heat and electricity paradigm to achieve a low carbon economy. The results truly highlight the benefits of an integrated energy system approach to decarbonization but modelling challenges for a problem of this scale are substantial and the tradeoffs are highlighted.

Hinker *et al.* in their contribution, *Precise Assessment of Technically Feasible Power Vector Interactions for Arbitrary Controllable Multi-Energy Systems*, address a very important and challenging modelling problem in the ESI space, that of ensuring feasibility to ensure applicability. They also evoke the energy hub and importantly make important references to market implementation.

The final paper of the seven by Heinen and O'Malley, *Complementarities of Supply and Demand Sides in Integrated Energy Systems*, explore the concept of a portfolio effect on the demand side in integrated energy systems. The planning problem posed to harness the increasing importance of distributed generation technologies to contribute to flexibility and adequacy highlights the difficulty of implementation in a market.

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