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Editorial

Synergies between energy supply networks

1. Introduction

The increasing share of variable renewable energy sources, strict targets set for the reduction of greenhouse gas emissions and the requirements on improvement of system security and reliability are calling for important changes in our energy systems. Energy systems have been in transition, extending their boundaries beyond the energy systems themselves, the 3-D interactive extensions, that relate to the dimensions of physical Space, Time scale and Human behaviors – STH extension. Under the new circumstance of the STH-demission, we need new approaches and solutions to solve the challenging issues associated with new transitions of future clean energy systems [1]. The next generation of competitive technologies and services that will create or enhance synergies between energy supply networks are being developed and matured. Facing these challenges and opportunities, energy supply networks (e.g. electric power networks, natural gas networks, hydrogen production and transportation, district heating and cooling systems, electrified transportation, and the associated information and communication infrastructure) are undergoing a radical transformation with massive investments in infrastructure and technologies [2]. This provides a window of opportunity. This transition is significantly increasing the coupling and interactions between energy supply networks via network coupling technologies, e.g. Combined Heat and Power units (CHP), Power to Gas (e.g. using excess renewable energy to produce hydrogen, which can be injected to the gas network or converted to synthetic natural gas, SNG, and then injected into the gas network) and Power to heat (e.g. heat pumps) processes. There is an urgent need to develop the next generation network coupling technologies and energy system integration methods which will make optimal use of synergies between energy networks to increase the hosting capacity and flexibility of distributed energy resources (DERs), enhanced demand response and support Smart Grid operation.

2. Synergies between energy supply networks

Conventionally different energy supply networks have relatively few interactions and were designed and operated independently. However, these diverse energy networks are increasingly interconnected with each other via network coupling technologies. The interactions mainly take place through conversion of energy between different energy vectors in order to provide services and ensure that each energy vector is managed in an optimal way. Fig. 1 shows some possible interactions between various energy supply networks and it can be seen that the network coupling technologies play a critical role in the energy system integration [3].

Energy system integration is urgently needed which uses a whole-system approach to optimize the synergies between energy supply networks in order to facilitate and coordinate the grid integration of DERs, while enabling the synergies and conflicts between the local distribution networks and the national level objectives to be understood and optimally coordinated. Innovative and competitive solutions of network coupling are also urgently required to enable and enhance the synergies and provide a significant amount of flexibility to energy networks. Some of the key challenges of exploiting the synergies between energy supply networks include:

- The complicated interactions and interdependencies between energy supply networks (technical, economic and markets) have not been clearly understood.
- There is no standard available for network coupling technologies and their network interfaces have significantly different characteristics.
- Design and operation planning of energy supply needs to consider the interactions and interdependencies between energy supply networks, to which there are no commercial tools available.
- The fragmented institutional and market structures of different energy systems is often a barrier to realise the benefits of synergies between energy networks.
- Integration of multiple energy supply networks would result in a more complex energy system to manage and operate. The interdependencies between different energy networks and the ICT (Information and Communication Technologies) infrastructure that facilitates interoperability would require powerful software models and analysis tools. It is argued that the integration of multiple energy supply networks may result in an energy supply system that is more susceptible to cascaded failures affecting reliability of supply.
- Network coupling technologies and solutions have been generally considered in the context of objectives and constraints at the distribution level, not necessarily reflecting on the impact on the design and operation of energy systems at the national level. Ignoring the interaction between distribution level energy networks and national infrastructure and objectives, will lead to significant cost and carbon inefficiencies and may compromise security of supply.

3. The Special Issue

This Special Issue in Applied Energy provides the latest research outcome in this promising and dynamic area of research and development, which focuses on the technological aspects.

Fig. 1. Possible interactions between different energy networks and integration of local renewables.

A total of 12 papers have been accepted for this Special Issue. The papers address a great variety of issues that can be put into three categories: (1) network coupling technologies; (2) analysis of synergies between energy supply networks; and (3) optimal use of synergies in network operation. The individual papers under each category are presented in detail below.

3.1. Network coupling technologies

The network coupling technologies physically link different energy supply networks and provide possibility and flexibility to optimize their synergies.

Power to Heat/Cooling technologies allow utilizing low cost electrical power for heat and/or cooling generation in periods of excess renewable electricity. A typical Power to Heat/Cooling system can be considered either a centralized system where energy conversion takes place in a large-scale plant and the thermal energy distributed using a pipeline network or a decentralized system where the energy conversion takes place closer to end user (see Fig. 2). In both systems, thermal energy storage facilities are used to decouple the time of heat production from demand. In centralized systems the storage facilities are integrated with heat/cooling distribution infrastructure such as district heating and district cooling networks. Power to Heat/Cooling systems are capable of utilizing surplus electricity from renewable plants and act as a controllable load that can ramp up/down or shut down quickly and provide interruptible capacity to the electrical power system.

Heat pumps have been recognized as one of the key technologies for decarbonizing the heating of domestic and non-domestic buildings. Paper [4] assesses and quantifies in a probabilistic way the impact of heat pumps and PV on the low-voltage distribution grid, as a function of building and district properties. The Monte Carlo approach is used to simulate an assortment of Belgian residential feeders, with varying size, cable type, heat pump and PV penetration rates, and buildings of different geometry and insulation quality. Modelica-based models simulate the dynamic

behavior of both buildings and heating systems, as well as three-phase unbalanced loading of the network. Stochastic occupant behavior is taken into account. It is shown that air-source heat pumps have a greater impact on the studied feeders than PV, in terms of loading and voltage magnitude. Furthermore, rural feeders are more prone to overloading and under-voltage problems than urban ones.

Power to Gas technologies convert electricity into hydrogen using an electrolysis process and subsequently to methane (SNG). The gas (hydrogen/methane) can be injected in the gas grid for energy storage and generation of power again or in the transport sector. Hydrogen and methane can be utilized in all well-established natural gas facilities (e.g. heating systems, CHP) and for heavy duty vehicles (trucks, trains, ships) as liquefied fuel (LNG). In addition, hydrogen can be utilized directly in industrial processes as chemical (e.g. ammonia synthesis) feed stock. Power to Gas is recognized as a long-term storage option, and it also provides additional benefits for power grid management. The conversion of surplus electricity into gas facilitates the transport of energy over long distances with low losses and makes effective use of the existing network of gas pipelines and underground storage facilities, as shown in Fig. 3.

In paper [5], techno-economic and Life Cycle Assessment of methane production via the combination of anaerobic digestion and Power to Gas technology were applied to sewage sludge valorization. Sensitivity analyses were carried out on biogas upgrading technologies, electricity prices, annual operation time and composition of the electricity mix with also a comparison between Power to Gas and direct injection. From an environmental point of view, continuous Power to Gas generates more greenhouse gases than direct injection, but intermittent operation with use of renewable electricity can significantly reduce emissions. Impact from continuous Power to Gas are higher than biogas upgrading, but much lower than fossil energy. Future development of low electricity consumption of the electrolysis process, and integration of renewable credits from CO₂ valorization can increase the competitiveness of this technology.

Fig. 2. Power to heat/cooling technologies.

Fig. 3. Power to gas and its utilization.

Fuel cell electric vehicles convert chemical energy of hydrogen into electricity to power their motor. Since cars are used for transport only during a small part of the time, energy stored in the on-board hydrogen tanks of fuel cell vehicles can be used to provide power when cars are parked. In paper [6], a community microgrid is presented with photovoltaic systems, wind turbines, and fuel cell electric vehicles that are used to provide vehicle-to-grid power when renewable power generation is scarce. Excess renewable power generation is used to produce hydrogen, which is stored in a refilling station. A central control system is designed to operate the system in such a way that the operational costs are minimized. A hybrid model for the system is derived, in which both the characteristics of the fuel cell vehicles and their traveling schedules are considered. The operational costs of the system are formulated considering the presence of uncertainty in the prediction of the load and renewable energy generation. A robust min-max model predictive control scheme was developed and a case study illustrates the performance of the designed system.

As one of the most successfully commercialized distributed energy resources (also as an important network coupling technology), the long-term effects of micro-turbines on the distribution network has not been fully investigated due to the complex thermo-fluid-mechanical energy conversion processes. In paper [7], a general modeling approach for micro-turbines is proposed, which allows for the long-term simulation of the distribution network with multiple micro-turbines. The feasibility of deriving a simplified micro-turbine model for long-term dynamic analysis of the distribution network is discussed, based on the physical understanding of dynamic processes that occurred within micro-turbines. A three-stage identification method was developed in order to obtain a piecewise micro-turbine model and predict

electro-mechanical system behaviors with saturation. Assisted with the electric power flow calculation tool, a fast simulation methodology is proposed to evaluate the long-term impact of multiple micro-turbines on the distribution network.

3.2. Analysis of synergies between energy supply networks

The synergies between different energy supply networks are analyzed by the following papers with various focuses.

Paper [8] presents the first multi-vector energy analysis for the interconnected energy systems of Great Britain (GB) and Ireland. Both systems share a common high penetration of wind power, but significantly different security of supply outlooks. Ireland is heavily dependent on gas imports from GB, giving significance to the interconnected aspect of the methodology in addition to the gas and power interactions analyzed. A fully realistic unit commitment and economic dispatch model coupled to an energy flow model of the gas supply network was developed. Extreme weather events driving increased domestic gas demand and low wind power output were utilized to increase gas supply network stress. Decreased wind profiles had a larger impact on system security than high domestic gas demand. However, the GB energy system was resilient during high demand periods but gas network stress limited the ramping capability of localized generating units.

In paper [9], a simulation model based on EnergyPLAN software with 2014 as the reference year was developed to represent Chongming's present energy structure. Four future scenarios which propose different further energy constructions have been observed. Results show that reductions in primary energy consumption, electricity import, annual operating costs as well as CO₂ emissions are realizable when switching to an energy system

with a high share of renewable sources combining natural gas Combined Heating and Power units. After preliminary discussions, the feasibility of different renewable sources penetration is analyzed through calculating the excess electricity production.

Paper [10] focuses on the flexible multi-generation systems (FMGs), which consist of integrated and flexibly operated facilities that provide multiple links between the different sectors of the energy system. This paper treats the design optimization of a conceptual FMG which integrated a methanol-producing biorefinery with an existing combined heat and power unit and industrial energy utility supply in the Danish city of Horsens. The objective was to optimize economic performance and minimize the total CO₂ emission of the FMG while it was required to meet the local district heating demand plus the thermal utility demand of the butchery.

Active demand side response will provide a significant opportunity to enhance the power system flexibility. Although electricity peak shaving has a clear reduction on required investments in the power system, the benefits on the gas supply network have not been examined. Using a Combined Gas and Electricity Networks expansion model (CGEN+), the impact of demand side response on the electricity and gas supply systems in GB was investigated in [11] for the time horizon from 2010 to 2050s. The results showed a significant reduction in the capacity of new gas-fired power plants, caused by electricity peak shaving. The reduction of gas-fired power plants achieved through demand side response consequently reduced the requirements for gas import capacity up to 90 million cubic meter per day by 2050. The cost savings resulted from the deployment of demand side response over a 50-year time horizon from 2010 was estimated to be around £60 billion for the GB power system. Although, the cost saving achieved in the gas network was not significant, it was shown that the demand side response will have a crucial role to play in the improvement of security of gas supply.

3.3. Optimal use of synergies in network operation

The optimal use of synergies is able to facilitate the integration of intermittent renewable energy generation, and improve network security and reliability in the operational domain.

Paper [12] introduces a coordinated scheduling strategy of the integrated energy supply networks. The electricity network and the gas network are modeled in detail, and the operation constraints of the networks are considered. The coordinated scheduling strategy optimizes the conflicting benefits of the electricity network and the gas network for daily operation while satisfying the operation constraints. A multi-objective optimization algorithm is applied to obtain a Pareto-optimal solution set, and a multiple attribute decision analysis using interval evidential reasoning was developed to determine a final optimal daily operation solution.

Accurate information regarding the uncertainty of short-term forecast for aggregate wind power is a key to efficient and cost effective integration of wind farms into power systems. Paper [13] presents a methodology for producing wind power forecast scenarios. Using historical wind power time series data and the Kernel Density Estimator, probabilistic wind power forecast scenarios were generated according to a rolling process. The improvement achieved in the accuracy of forecasts through frequent updating of the forecasts taking into account the latest realized wind power was quantified. The forecast scenarios produced by the proposed method were used as inputs to a unit commitment and optimal dispatch model in order to investigate how the uncertainty in wind forecast affect the operation of power system and in particular gas-fired generators.

Integrated heat and electricity dispatch is crucial to exploit synergistic benefits from integrated energy systems. However, this requires information from both electricity systems and district heating systems, which are managed by an electricity control center and district heating control centers. For reasons pertaining to privacy, communication, dimension, and compatibility, it is not practical for district heating control centers to send detailed models to the electricity control center. Therefore, a new feasible region method is proposed in [14] for formulation of new district heating system models, which exploit the flexibility of district heating systems with consideration of building thermal inertia.

With the increasing installed capacity of wind power and the interdependencies among multiple energy sectors, optimal operation of integrated energy systems with combined cooling, heating and power (CCHP) is becoming more important. Paper [15] proposes an optimal dispatch strategy for the integrated energy system with CCHP and wind power. Natural gas system is modeled and its security constraints are integrated into the optimal dispatch model. The gas shift factor matrix for natural gas system is derived to quantify the impact of gas supply and load at each node on the gas flow through the pipelines so that the pipeline flow equation is linearized.

4. Conclusions

The papers in this Special Issue cover the landscape of research gaps and opportunities, research activities, analysis methods, and the potential techno-economic benefits in the use of synergies between energy supply networks. The results of these papers provide a better understanding, quantification and optimization of the interdependencies and interactions between energy supply networks. The outcome of the research shows that the synergies between energy networks have a huge potential to facilitate achieving a more low-carbon, secure, reliable, flexible and affordable energy future.

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